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FACTORS GOVERNING DIFFERENT TYPES OF PRECIPITATION

Arthur C. W. Baskin

Thesis
B242355
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FACTORS GOVERNING DIFFERENT TYPES OF PRECIPITATION

Submitted in partial fulfillment of the
requirements for the degree of Master of Science
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California Institute of Technology
Pasadena, Calif.
1937

T242355
C.1

Factors Governing Different Types of Precipitation.

The question of just what causes precipitation in general, and what causes a particular type of precipitation has interested man for many ages and will probably always interest him since man's prosperity, contentment and in most cases his very existence depends on the fall of precipitation of favorable type and quantity.

In considering precipitation the following classifications are suggested:-

A. Classification according to the form and appearance of the individual particles, ie, morphologically, as rain, snow, sleet, hail, etc.

B. Classification as to air mass conditions, or combined frontal and air mass conditions, which cause the lifting and cooling which finally result in precipitation, such as:-

1. Air mass conditions.
    a. Potentially instable, becoming instable.
        1. Shower type precipitation caused by convection due to surface heating alone sufficient to initiate free convection to the ice crystal level.
        2. Precipitation from thunderstorms caused by convection due to surface heating alone sufficient to initiate free convection.
        3. Shower type precipitation caused by orographical lifting sufficient to initiate free convection.
        4. Precipitation from thunderstorms caused by orographical lifting sufficient to initiate free convection.
    b. Stable air mass, remaining stable.
        1. Precipitation caused by sufficient orographical lifting either to reach ice crystal level or to cause sufficient condensation to produce precipitation.

11. Frontal Conditions.

- a. Warm front or cold front precipitation involving stable air.
    - 1. Warm front type - steady precipitation.
    - 2. Cold " " " "
    - 3. Warm " " - occlusion - steady precipitation.
    - 4. Cold front type occlusion - " "
    - 5. Pre-frontal orographical precipitation.
- b. Warm front or cold front precipitation involving unstable air.
    - 1. Warm front type intermittent precipitation.
    - 2. Warm front type thunderstorm precipitation.
    - 3. Cold " " showery "
    - 4. Cold " " thunderstorm "
    - 5. Warm " " occlusion showery type precipitation or thunderstorm precipitation.
    - 6. Cold front type occlusion showery type or thunderstorm type precipitation.

A further classification of precipitation from the standpoint of intensity may be made, the various degrees being mist, drizzle, light, moderate, or heavy, etc. The factors which determine the intensity and duration of precipitation will be discussed later.

A survey of the problem of factors governing different types of precipitation soon reveals that investigation of the formation of different morphological types of precipitation is handicapped by:

1. Scarcity of sounding data for immediately before, during, and after the formation of a morphological type, and at the precise level where the precipitation is forming.
2. Lack of observations taken in the very turbulent regions of thunderstorms due to the danger to airplanes of the severe turbulence. Vertical velocities over 100 meters per second must have been required to support some hailstones which have fallen.

3. The degree of accuracy of instruments usually carried aloft is not up to laboratory standards. This is especially true of the hair hygrometer which, as is well known, gives erroneous readings at low temperatures.

4. At present only a confusing maze of theories, many based on laboratory and other experiments, however, exist for the explanation of the formation of raindrops from the condensation on fine nuclei in the air and for the explanation of the formation of snowflakes and large rain drops.

Following is a brief summary of some of the theories concerning the formation of raindrops.

Bennett (1) concludes that:-

1st. The nature of the nuclei of condensation.

Considerable doubt still exists concerning the nature of the nuclei of condensation in the air. Microscopic examination of nuclei found in fog particles reveals singly refracting crystals, presumably of sulphates, chlorides, nitrates and chloride salts. Experiments by Wigand and Boylan seem to show that ordinary dust particles do not act as nuclei, even in a supersaturated atmosphere. Presumably it is only the water soluble salts which act as nuclei, either dry or in the form of solutions or hydrates.

2nd. The source of nuclei - two possibilities - the sea and smoke.

3rd. The properties of the nuclei.

If the water vapor pressure which they exert in the zone of atmosphere immediately surrounding them is less than in the atmosphere in general, water will tend to condense on the nuclei; if it is greater, water will tend to evaporate from the nuclei. If water is present, its vapor pressure will differ from the vapor pressure over a plane surface of pure water due to three effects, namely (1) the convex curvature of a drop (hence the size of a drop effects the vapor pressure), a drop of pure water of radius 10^{-5} cm and temperature 10° C would have a vapor pressure of 1.2 per cent above saturation over a plane surface, and a drop of 10^{-6} cm, 12.7 per cent above. (2) The presence of the salt in solution would lower the vapor pressure. (3) An electric charge on the nucleus will decrease its vapor pressure. Thus if a nucleus in equilibrium with an atmosphere of given relative humidity were to increase in size, two opposing forces would come into play and it seems impossible, in a particular case, to say whether or not the resultant tendency would be for the vapor pressure to rise and hence for the drop to revert to its original size.

(1) M. G. Bennett: Quarterly Journal of the Royal Meteorological Society. Vol. LX No. 253 Jan. 1934.

4th. The production of raindrops.

By Stoke's Law the Velocity (cm per second) of falling droplets varies with their radius (cm) as follows:- $V = 1.21 \times 10^{6} r^{2}$ where r - the radius of the drop in cm. Hence small fog droplets fall so slowly that they may seem almost permanently suspended, and even in case of larger cloud droplets a current of air rising with a fairly small velocity can maintain them at a constant height or even carry them aloft. Consider then how the larger drops, which fall out as precipitation, are formed. As Simpson (2) pointed out:-

(1) The nuclei may grow continuously by condensation only to a certain definite size depending largely on the type of nuclei.

(2) Only drops of the same salt solution may unite.

Evidence for abandoning the belief that drops may grow continuously in increasing relative humidities up to the maximum possible size of raindrops has not yet been produced.

The agencies which seem to affect the coagulation of fog or stratus particles into rain seem to be:-

(1) Turbulence - which tends to force drops together mechanically.

(2) The viscosity of the air - which permits larger droplets to fall faster than small ones and to overtake and collide with them.

(3) The electric force of repulsion when the drops carry like charges tends to prevent coagulation of drops.

(2) G. C. Simpson, Brit. Ass. Adv. Sci., Leicester Meeting, 1933.

A theory of Humphrey's (3) which is well known regards the formation of raindrops as due to "selective filtration" of the nuclei by the sinking of nuclei relative to the air after water condenses on them so that as the air is lifted higher fewer and fewer nuclei remain, and consequently the remaining moisture condenses in larger and larger drops on the remaining nuclei.

(3) W. T. Humphreys - Physics of the Air (1929) pages 264 and 265.

Bergeron (4) favors the ice crystal theory. Briefly, this theory states the mechanism for the formation of precipitation in cumulo - nimbus clouds is that ice crystals from the top of the cloud drop down into the water part of the cloud. The small water droplets gather over the ice crystals and form raindrops, however, if the water in the cloud is under-cooled, then the ice crystals gather under-cooled droplets which immediately freeze into snow or ice. The latter case will be discussed in more detail in connection with the formation of snow or hail.

The ice crystal theory is plainly not applicable to drizzle and other light precipitation from stratus and strato-cumulus lying well below the ice crystal level and when prolonged over a period of about a day the quantity of rainfall from these sources can become fairly large.

A theory of the formation of raindrops and snowflakes which has never been completely disproved is that of Pick (5). It is that ascent of air (accomplished by any means) is accompanied by expansion and cooling. When the dew point is reached, condensation occurs on the nuclei present. The droplets formed at first are very small, probably of the order of 0.002 mm. and thus they are carried upward with the rising air. Further ascent means further cooling and more condensation of water on the drops. When the diameter reaches 0.2 mm, the drops are falling relative to the air at the rate of about 1 meter per second which is more rapid than air currents normally rise and thus precipitation occurs from the cloud.

When condensation occurs only after the freezing point is reached, the water vapor condenses, first, into liquid drops of sub-cooled water which crystalize afterward. Once the first crystals are formed, further condensation takes place, but now the vapor condenses directly into the solid form without going through the intermediate liquid stage. This water vapor crystalizes into hexagonal form and snow flakes are formed of one or more crystals. Simpson's conclusion (6) that sub-cooled water exists at much lower temperature than is generally thought possible was arrived at from a study of fogs and iridescent clouds seen in the Antarctic. He describes an occasion on which he was enveloped in a fog during sunshine. The surface temperature was - 21°F. A white bow appeared, similar to a rain bow. His conclusion is that the effects observed in the fog could only be produced by the refraction of light by small spheres and that therefore super-cooled water droplets must have been present.

(5) W. H. Pick - A Short Course in Elementary Meteorology (1920)

(6) G. H. Simpson - Quarterly Journal of the Royal Meteorological Society. Vol. 38 Page 291 (1912).

He then states that a similar chemical condition is frequently found in which "when a new phase which is finally solid, makes its appearance suddenly, whether from vapor or solution, it appears first as a liquid and it may run through many intermediate (labile) forms before reaching its final solid form. Sulpher, for instance, forms globules, which crystallize later."

Before proceeding further it is advisable to consider the stability of the atmosphere and the factors affecting it.

The degrees of stability in the atmosphere and the manner in which it is altered is very important to the formation of precipitation since the degree of stability of the atmosphere contributes materially to the production of turbulence and vertical convections.

The effects of lifting or sinking, convergence or divergence of air mass layers are:-

For a stable layer;

Whether the layer be saturated or unsaturated, lifting decreases stability, but can never cause the layer to become unstable; sinking increases stability.

Divergent flow increases the stability of a stable layer, increases the instability of an unstable layer, dry or saturated.

Convergent flow decreases stability of a stable layer and decreases the instability of an unstable layer, dry or saturated.

For unstable air;

Lifting decreases the instability before saturation but increases it after saturation.

Sinking increases the instability before saturation but decreases it for a saturated layer.

For potentially unstable air;

The effects of lifting and sinking are naturally the same as for stable air before saturation and the same as those for unstable air after saturation.

Morphological Types of Precipitation.

1. Mist consists of gentle precipitation of moisture particles barely larger than fog particles. Its intensity of fall in millimeters per hour is of the order of 0.05.

Mist may fall from low level stratus or strato-cumulus clouds in case of gentle lifting and turbulence, or it may be the result of partial evaporation in the lower levels of the atmosphere of snow or light rain falling from higher clouds especially alto-stratus. The sounding for Murfreesboro, Tenn. for 9 February, 1937, (page30) illustrates mist due due to the latter reason. This sounding shows an alto-stratus overcast condition from 2860 to beyond 3990 meters. From 3990 to 3500 meters icing conditions prevail, from 2220 to 1800 meters is the snow region, from 1800 to 1080 meters is a region of light rain, from 1080 meters to 700 meters only light mist prevails due to the partial evaporation of the falling light rain. Below 700 meters no precipitation is occurring as yet since the mist is completely evaporated below this level. Of course, with the continuation of the precipitation from higher levels (due to overrunning of warm moist air over a warm front) the mist soon reached the surface and was closely followed by light to moderate rain.

Mist originating from stratus or strato-cumulus clouds is much more common than that due to partial evaporation of light rain or snow from higher levels since usually the evaporation process is either so complete that no precipitation of any kind reaches the surface or the evaporation process is so ineffective that precipitation of particles of larger size than mist occurs.

Mist is usually caused by a marked onshore drift of warm, moist but fairly stable maritime air, accompanied by gentle lifting and turbulence.

Mist generally occurs at night, especially soon after sunset. The effect of radiation from the cloud top is to cool it and thus to increase the lapse rate and cause some instability. Mist or light drizzle may result also from the sudden formation of lower cloud systems in Polar Continental air in winter, due principally to the gradual lifting of this air in the convergent zone near a front Polar Continental air in winter has very high relative humidities and very little lifting is necessary to saturate it. If this lifting occurs at night then ceilings and visibilities will drop very rapidly due to the mist or drizzle.

(2) Drizzle consists of small droplets of the order of 0.2mm in diameter which are so numerous that they seem to fill the air. Drizzle usually falls fairly gently; its intensity of fall being about 0.25 mm per hour. Like mist it may be due to partial evaporation of precipitation from higher stratus or strato-cumulus levels but it usually falls from fairly thick stratus or strato-cumulus clouds. Like mist it is usually caused by advection of a rather thick layer of warm, moist but fairly stable maritime air, accompanied by lifting due to convergence or to orographical causes with sufficient turbulence to cause the cloud particles, especially those in the lower and denser part of the cloud, to coalesce due to mechanical forces causing collisions.

It seems reasonable to believe that the size of the droplets will depend largely on the thickness of the saturated layer and on the amount of turbulence agitating it. It would thus appear that drizzle or light orographical rain in stable air is a function of the thickness of a stratus or strato-cumulus layer and the degree of turbulence within it. In the case of non-orographical mist or drizzle the stratus level is usually lower, the clouds thinner, and the lifting and turbulence less than in the case of light orographical precipitation.

The fact that almost any light rain is called drizzle by many observers sometimes renders it difficult to judge whether or not a station reporting drizzle is in the warm sector of a nearby cyclone.

The following table represents the distinctions between certain different types of precipitation largely from the standpoint of intensity of fall.

Air Density at 0°C and 988 m.b.

Popular Name	Intensity m.m./hr.	Diameter of Drops m.m.	Terminal Velocity V m/sec	Milligrams of Liquid Water in Cloud Per cu. meter	Height of Cloud Above Surface in Meters
Fog	Trace	0.01	0.003	6.0	0
Mist	0.05	0.1	0.25	55.5	100
Drizzle	0.25	0.2	0.75	92.6	200
Lt. Rain	1.00	0.45	2.00	138.9	600
Mod. Rain	4.00	1.00	4.00	277.8	600
Heavy Rain	16.00	1.5	5.00	333.9	1000
Excessive Rain	40.00	2.1	6.00	1851.9	1200
Cloudburst	100.00	3.0	7.00	5401.4	1200
		5.0	8.00		

As can be seen from the table, raindrops vary in size from about 0.45 to about 5.0 mm. Various theories for the manner of formation of raindrops have been given. It appears that some of the theories are more applicable to light, small drop precipitation from well below the ice crystal level while others involving the ice crystal theory account more perfectly for the formation of large drop precipitation.

The chief requirements for the formation of rain instead of some frozen type of precipitation is that the condensation level lie well below the ice crystal

level and that the

accelerated rising vertical currents not continue very far beyond the ice crystal level.

The steps in the formation of rain of the smaller sizes of droplets which are still larger than drizzle droplets seem to be orographical or other lifting of fairly stable but moist air, the formation of thick stratus or straro-cumulus clouds and fairly active turbulence within the clouds. As stated previously it is believed that the size of the drops depend on the amount of lifting, the thickness and density of the clouds formed, and the degree of turbulence in the clouds.

(4) Snow consists of precipitation in the form of flakes consisting of one or more ice crystals which form an infinite variety of patterns. If snow falls when the temperature is comparatively high, large wet flakes fall since some melting is taking place; with lower temperature, the flakes are smaller and dryer.

Conditions favoring the fall or snow are:

(a) The ice crystal level close to the ground or temperatures below freezing at the ground, and (b) condensation not occurring until above the ice crystal level, and (c) moderate to strong turbulence in the cloud region. With temperatures near the ground much above 0°C any falling snow will melt and the precipitation willbe in the form of rain. In many cases the temperatures near the ground are high enough to melt and evaporate the snow and rain unless the specific humidity within the cloud is high enough and the condensation level fairly low. Sheets of falling snow and rain which never reach the ground are occasionally observed in the sky.

The conditions aremost easily met (a) by frontal conditions involving two polar air masses in winter, such as air masses of Polar Pacific and Polar Continental origin, or (b) by instability set up in a Polar Pacific or Polar Continental air mass in winter or early spring by orographical lifting, especially if the air mass has had recent water trajectory as in the case of fairly fresh Polar Pacific air lifted as it flows inland into

Washington and Oregon, or in the case of Polar Continental air after passage over the Great Lakes which heats the air slightly and adds moisture to the lower levels.

HAIL

(5) Hail is generally divided into two classifications: soft hail, or "graupel", and hail, meaning hard hail. "Graupel" consists of semi-transparent lumps composed of a soft core of white ice or granulated snow and a thin hard coat of clear ice. They are usually round, but are sometimes conical. They are fairly hard but can be compressed between the fingers to some extent. "Graupel" frequently occur along with raindrops for reasons which will be discussed later. Hail, ie, hard hail, is of the same construction as soft hail except that it has many layers of clear ice around the same type of core. Actually, as will be seen from a consideration of how hail is formed, there is an infinite degree of variation in hailstones, simply depending on the number of alternate layers of clear ice and soft ice or snow around the core.

For the formation of hail the chief requirements are:- that vertical velocity somewhat greater than that required to hold raindrops aloft must exist at the ice crystal level, that condensation occur below the ice crystal level and that the vertical velocities must continue to accelerate rapidly for a long distance beyond the ice crystal level.

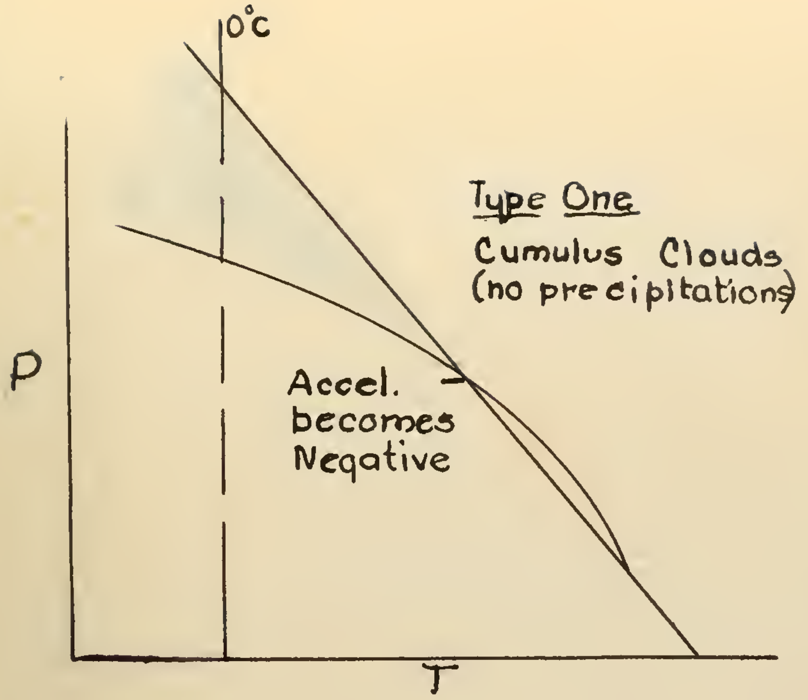
Ice crystals and sub-cooled water exist together for some distance beyond the ice crystal level. The extent of this region is not known. The state is an unstable one. If a sub-cooled droplet strikes an ice crystal it at once solidifies, but at the same time imprisons a little air. The ice crystal increases in size and will begin to fall if the velocity of the ascending air is not too great. As it falls through the sub-cooled water region it grows still more and imprisons more air, arriving at the bottom of the sub-cooled zone as a ball of soft ice. If the velocity of fall through the sub-cooled zone has been great, it arrives at the region where the temperature is just 0°C, with its own temperature below 0°C. Consequently, any further falling means that water which is present in a non sub-cooled state at and below the ice crystal level is deposited upon it in a uniform layer which quickly freezes into a hard transparent coating with little or no air imprisoned in it. Vertical currents and turbulence may be sufficient to carry the hail stone again into the region of sub-cooled water, a layer of soft ice being formed around the previous transparent layer. This process may be repeated until vertical currents can no longer sustain the falling hailstones and they reach the ground.

In the case of soft hail it is apparent that the vertical velocity at the ice crystal level is very little morethan the 8 meters per second required to sustain large raindrops and the acceleration decreases rapidly above the ice crystal level. The fact that soft hail frequently falls along with some rain indicates that vertical velocities at the ice crystal level are fluctuating from just above the 8 meters per second requirement to sustain large raindrops to below this value or that some melting of the hail is taking place.

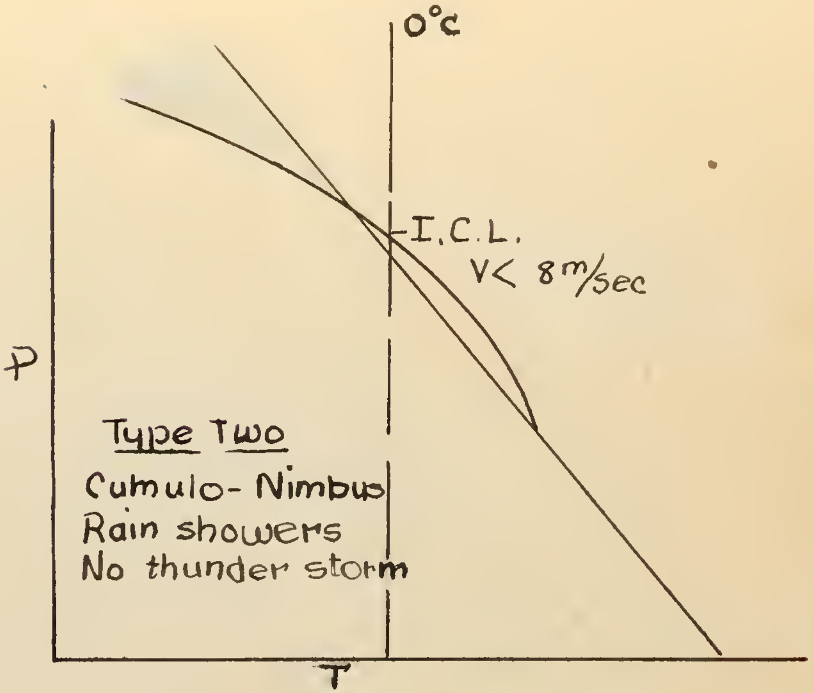
It is well known that there must be regions of compensating down currents whenever we have vertical currents. Airplane pilots have frequently observed the sudden changes in acceleration and velocity as they pass from one cumulo-nimbus cloud to another. The clear space between clouds is the region of the strongest down currents. The smaller the distance between the cumulo-nimbus clouds, the greater the downward current between them.

SLEET

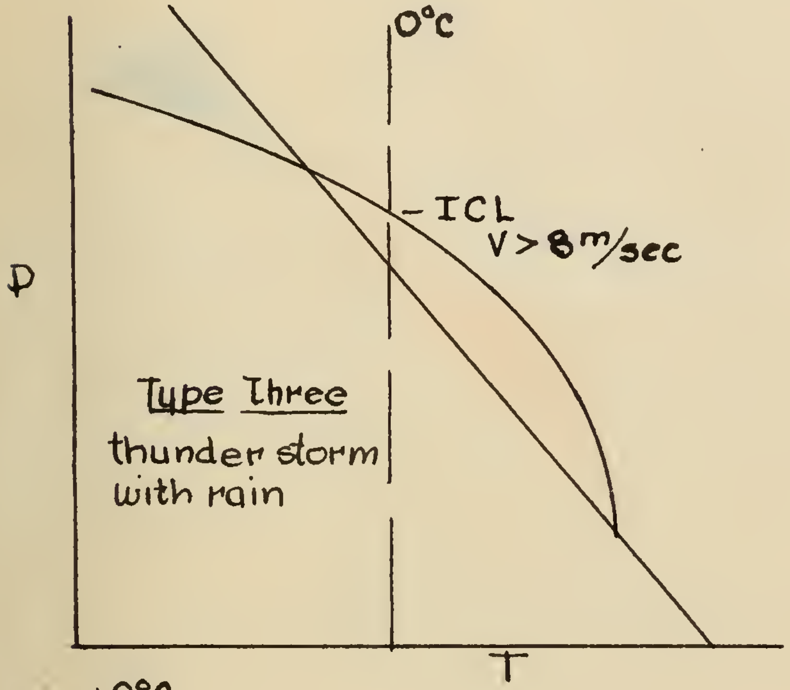
(6) Sleet consists of precipitation in the form of ice pellets and is formed by the freezing of raindrops or melted snowflakes as they fall through a cold air mass having temperatures well below freezing. It is usually the result of frontal overrunning of warm moist air, such as a Tropical Gulf air (as TG_2)



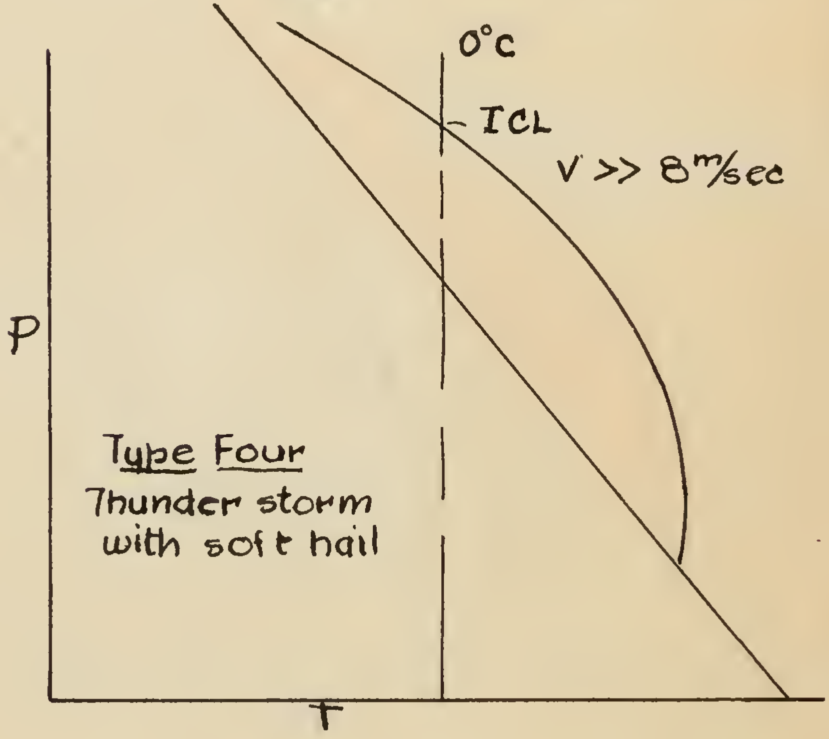
Type One
Cumulus Clouds
(no precipitations)



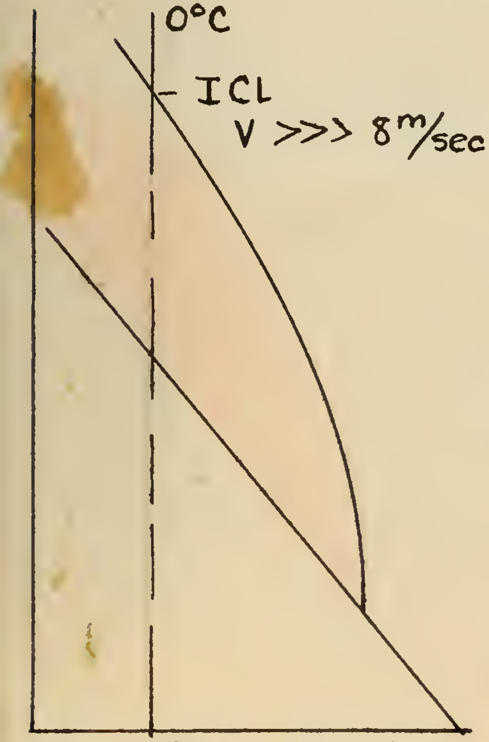
Type Two
Cumulo-Nimbus
Rain showers
No thunder storm



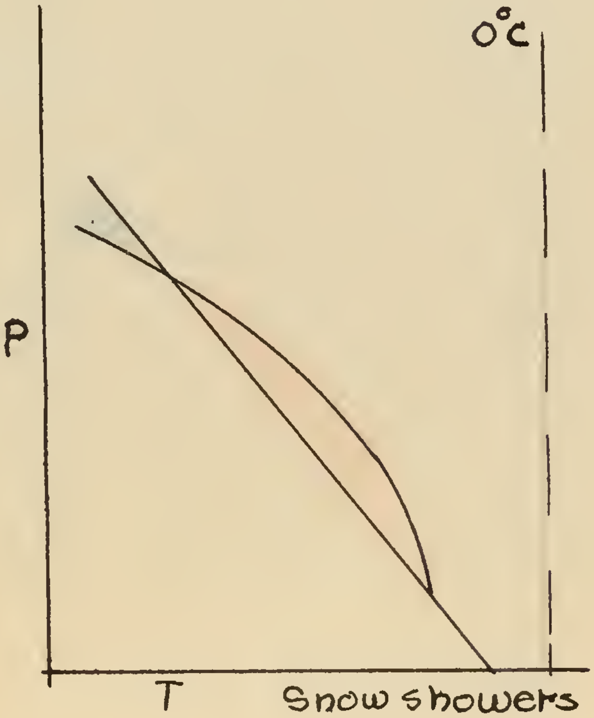
Type Three
thunder storm
with rain



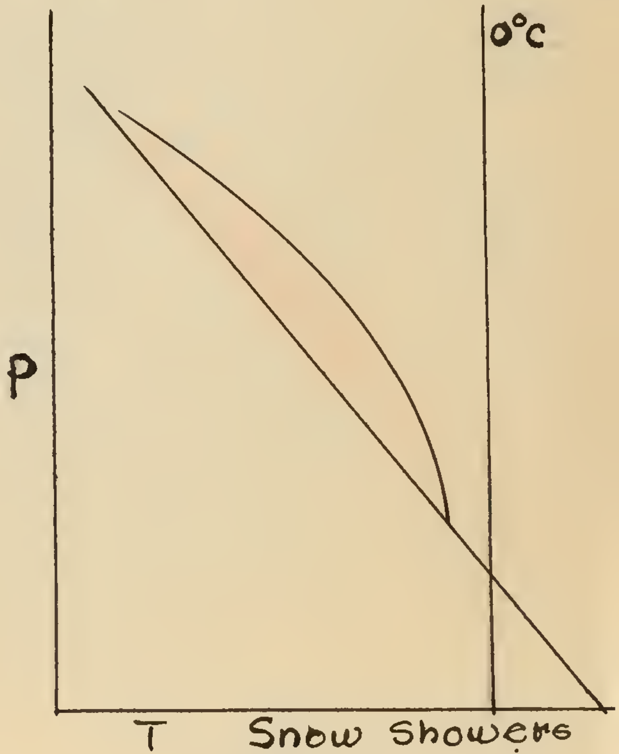
Type Four
Thunder storm
with soft hail



Type Five - Thunder
storm with hail



Snow showers



Snow showers
changing to rain
showers

over an air mass with temperatures well below freezing at the surface, such as a Polar Continental air (asPC_2). The frontal surface regions at and above the condensation level in such a case present the worst conditions for icing of aircraft.

USE OF ADIABATIC CHART FOR DETERMINING INSTABILITY PHENOMENA.

From consideration of soundings taken previous to the occurrence of various instability phenomena it appears that useful distinctions can be made between the requirements for cumulus cloud formation, showers, thunderstorm with rain, thunderstorm with soft hail, and thunderstorm with hard hail. Type one situation represents conditions for the formation of cumulus but no precipitation. Here a small positive area exists causing convection, but a sufficiently large negative area above this insures that the clouds cannot extend to the ice crystal level.

Type two represents conditions favoring the formation of cumulo-nimbus showers. The ascent curve in this case as in all the cases represents the actual ascent curve corrected for probable lift, for effects of divergence or convergence and altered according to expected variations in specific humidity, as due to an expected water trajectory before the air of the sounding reaches the forecast region.

In type two, the ice crystal level lies within the positive area and sufficient positive area lies below it to allow vertical velocity less than the 8 meters per second necessary to support large raindrops. No lightening occurs since the velocity at the ice crystal level is insufficient to break up raindrops and to establish by so doing differences in potential which are large enough to cause lightening. No hail occurs since the vertical velocity cannot sustain even raindrops.

In type three, a thunderstorm with precipitation as rain would occur. Here the ice crystal level lies within the positive area in such a way that a fairly large part of the positive area lies below the ice crystal level and a relatively small part lies above the ice crystal level, the acceleration of the rising particle changing to negative a relatively short distance above it.

Sufficient turbulence and vertical velocity in excess of 8 meters per second exist at the ice crystal level to split raindrops in sufficient quantity to cause lightening but vertical velocities are insufficient to cause the formation of hail in any form.

Type four is similar to type three except that vertical velocities much greater than 8 meters per second exist and the acceleration remains positive up to higher levels. In this case a thunderstorm would occur accompanying the fall of soft hail or soft hail and rain.

In type five a thunderstorm would occur with the precipitation in the form of hard hail, the size of the hail stones depending on the magnitude of the vertical velocities reached beyond the ice crystal level, the vertical velocities at the ice crystal level being very much greater than 8 meters per second.

A consideration of the adiabatic chart shows that the longest positive areas are formed when the temperature lapse rate is very large, approaching the dry adiabatic from within the lowest two kilometers extending upward without inversions, and if lower parts of this region of steep lapse rate are very moist so that they will start following the moist adiabatic after only a very short lift.

These conditions exist in case of sufficient lifting of very warm and moist Tropical Gulf air in the lower two kilometers overrun by very dry air, such as an old Polar air which has been subject to a great deal of subsidence.

All the conditions can be covered by simply stating that a large positive area is formed and the indicated energy is realized if the lapse rate of equivalent potential temperature is excessive at low levels, and if sufficient lifting is available to saturate the lower part of the region characterized by negative $\frac{d\theta_e}{dz}$. Severe thunderstorms occurred in Missouri on 29 April, 1937, when the lifted air showed that the kilometer just above 1160 meters had a lapse rate of equivalent potential temperature of 27°C per kilometer. A lift of only 800 meters was required to saturate the 1160 meter level and this lifting was easily accomplished by the air being squeezed between an advancing cold front and a retrograde warm front. Hail stones two inches in diameter fell at Columbia, Missouri.

As previously stated for a thunderstorm to occur the condensation level must be below the ice crystal level and the ice crystal level must have sufficient positive area below it to insure vertical velocities sufficient to violently disrupt raindrops and to thus establish sufficient differences of potential.

In considering the positive areas on adiabatic charts representing the energy available due to temperature differences, level for level, between the ascent curve as corrected for probable lift, for probable effects of divergence or convergence, and for probable addition of moisture to the lower levels, it soon becomes apparent that a relatively small positive area at lower levels is as effective as a relatively larger positive area at higher levels. The reason for this becomes apparent when we consider the equation for acceleration due to differences in density.

(1) $$A = \frac{g(\rho_2 - \rho_1)}{\rho_1}$$

But $P = \rho R T$

The air layers of particles being considered are assumed to be at about the same Pressure since they are in the same vicinity and at the same level, therefore, P is considered constant.

Substituting: $$A_0 = \frac{\frac{gP}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)}{\frac{1}{T_1}} = \frac{gP_0}{R}\left(\frac{T_1 - T_2}{T_2}\right)_0$$

A at some other level h = $A_h = \frac{gP_h}{R}\left(\frac{T_1 - T_2}{T_2}\right)_h$

comparing A_h with A_0 for a 1° temperature difference at each level, ie, using $T_1 - T_2 = 1°$ and neglecting the very small error introduced due to failing to use a gas constant R in each case which depends on the water vapor content, ie, considering the R's as equal for all levels under consideration then:

$$\frac{A_h}{A_o} = \frac{(P)_h}{(P)_o} \times \frac{(T_2)_o}{(T_2)_h}$$

This resultsin a comparison of the acceleration resulting at one level per degree difference in temperature between the rising air layer or particle and its surroundings with the acceleration resulting from the same difference in temperature at any other level.

If $P_o = 900 mb$ and $P_h = 450 mb$ and if $(T_2)_o = 293°$ and $(T_2)_h = 253°$ (the lapse rate being assumed to be about half way between the dry and the moist adiabatic) then $\frac{A_{450mb}}{A_{900mb}} = \frac{450}{900} \times \frac{293}{253} = .5 \times 1.16 = .58$

If $P_o = 900 mb$, $P_h = 800 mb$, $(T_2)_o = 293°$, $(T_2)_h = 285.5°$

then $\frac{A_{800mb}}{A_{900mb}} = .889 \times 1.027 = .914$

It is seen that the change in acceleration with elevation for a 1° difference between the temperature of rising layers or particles and the temperature of the surrounding air (as shown by the corrected ascent curve) is largely due to the change in pressure, the effect due to the decrease in temperature with elevation being to tend to increase the acceleration produced as elevation is increased.

It would be highly desirable to devise a rapid and fairly accurate means of determining the vertical velocities which would result at different levels in case the energy indicated by a positive area is made available. Such determination of the vertical velocity is not now possible, but conclusions can be drawn from the size and vertical extent of the positive area.

In view of the fact that very little data is available which is suitable for use as a basis for investigation of the causes of many of the morphological types of precipitation and since up to now no one has entirely explained even the formation of raindrops and snowflakes, it seems advisable to investigate the various frontal and air mass conditions with which precipitation is associated noting any facts which become apparent regarding the factors affecting different morphological types of precipitation.

THE EFFECT OF MOUNTAIN RANGES ON STABLE AND UNSTABLE AIR MASSES

(Extracts from a paper by Dr. Irving P. Krick, are included herein.)

Particles in a stable air mass resist vertical motion and hence tend to resist passage over a mountain. If there is a horizontal outlet available around the mountain then the stable air mass will flow around rather than over the mountain. However, if no horizontal outlet is available, the gradient must be such that sufficient energy is available to accomplish the work required in raising the air to the top of the mountain before a flow over the mountain will result. Normally, the stable air simply curves around the obstacle, entirely avoiding any vertical displacement. But if a long mountain range stands in the way, then a damming up of the air flow results. This is shown on the synoptic maps by high pressure on the windward side of the ranges and low pressure on the leeward side. No wind velocities over the ranges occur, however, which are comparable to that which the existing pressure gradient would normally indicate. In this case, the mountain ranges prevent the realization of the potential energy of the air masses by preventing their contact at lower levels. The pressure gradient merely indicates, in this case, that the air masses on the two sides of the mountains are of different weight.

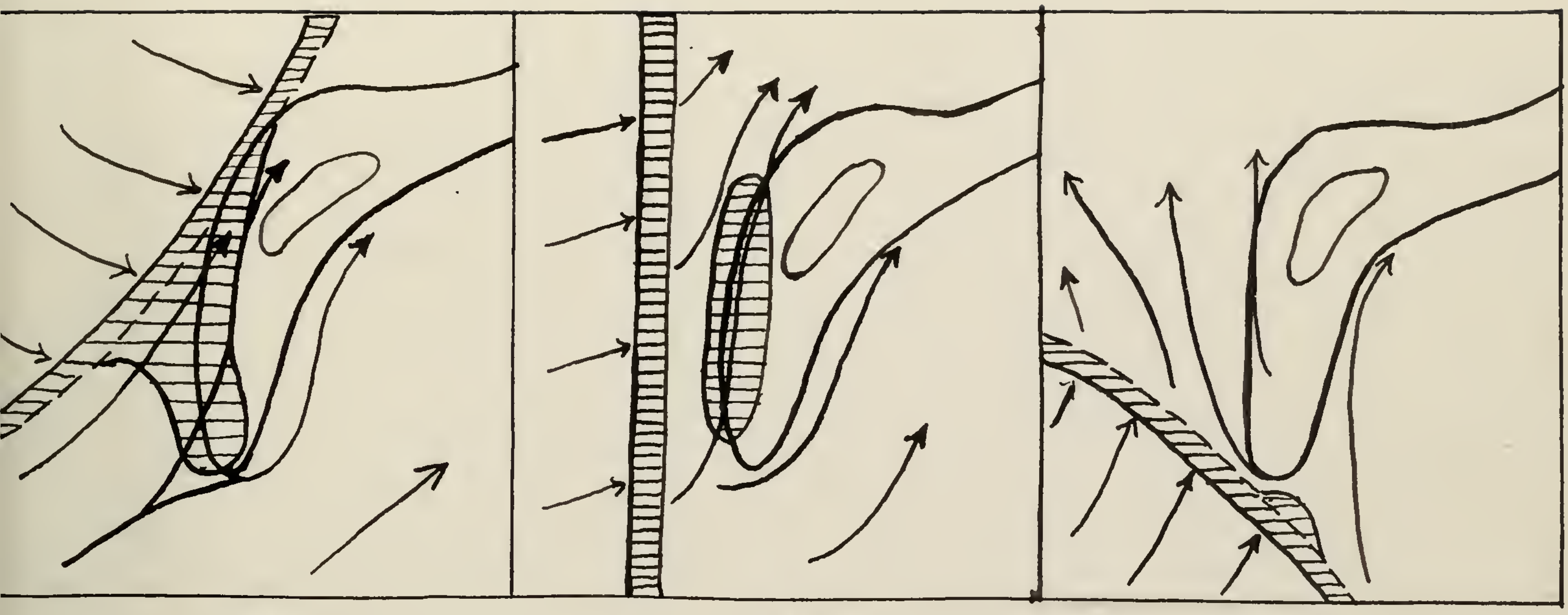
In unstable air, however, the upward impetus which it is given on reaching the mountains is retained and acceleration continues, the unstable air flowing readily over the mountain ranges. This effect has been photographed with movie camera and when shown with the sequences speeded up greatly, billows of clouds seem to pour over mountain tops giving the appearance of water flowing over a dam.

If flowing against an extensive mountain range, all the air can not escape laterally; some air must ascend, even in the case of stable air masses. If the ascent is sufficient, then the condensation level is reached and cloudiness occurs - the type depending on whether or not the air mass is stable:- stratiform clouds in case of stable air mass; cumulo form clouds in case of unstable air mass. If lifting is continued orographical precipitation occurs. The orographical precipitation will be of a fairly steady type if resulting from a stable air mass, as in the case of stable tropical pacific or tropical maritime air being forced aloft.

In case of an unstable air mass, such as fresh Polar Pacific, snow or rain showers occur. The rainfall in this case is usually much heavier than in the stable case. In the stable case the air resists vertical displacement and curves around the mountains as best it can while in the unstable case the air does not resist the vertical movements initiated by the mountains, and hence is better able to produce precipitation. The showers occurring at sea are retarded by the passage of the air mass inland, hence the distances between showers moving inland is decreased and a piling up against the mountains results.

The convergence of air passing around a mountain corner has been found to result in a sort of light orographical precipitation. Easterly currents passing around the southern extremity of the Scandinavian ranges frequently give rise to strong local gales accompanied by light rain or snow fall entirely independent of any frontal cause.

A good example of orographical precipitation in unstable air passing over high mountains is found in the India Monsoon during the summer months. This air which blows in off the Indian Ocean is very warm and moist, and is convectively unstable. Upon passage inland it is heated from the ground and becomes even more unstable. When it reaches the Himalaya Mountains it is forced to ascend and heavy instability type precipitation results. Due to its extreme initial convective instability it requires only a small lift (or cooling) to relieve it of large quantities of moisture. It must continue to climb so high in surmounting these mountains that by the time it reaches the plateaus of Tibet it is too dry to give any more precipitation.

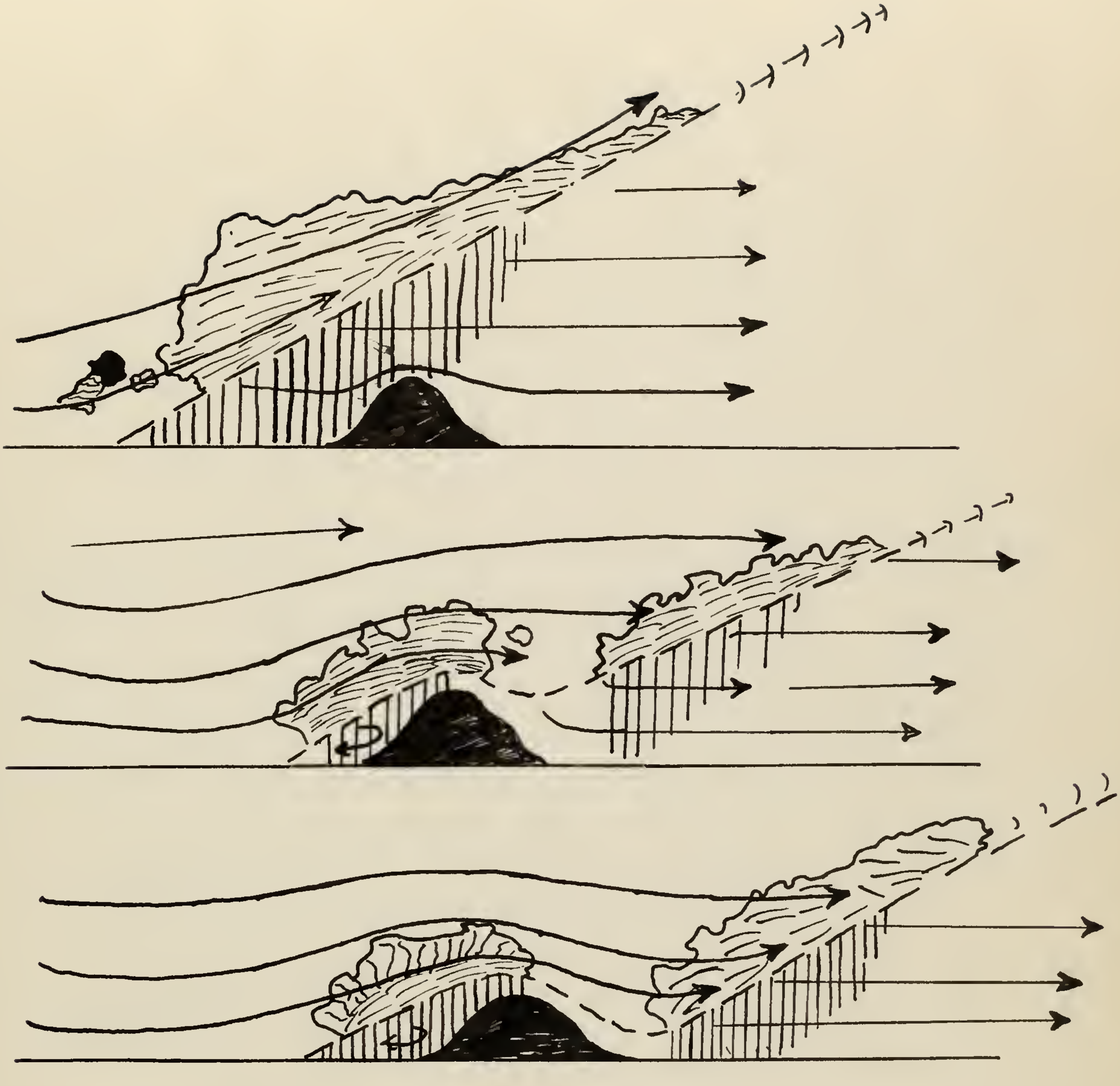


a. b. c.

Combined orographical precipitation and cold front precipitation,

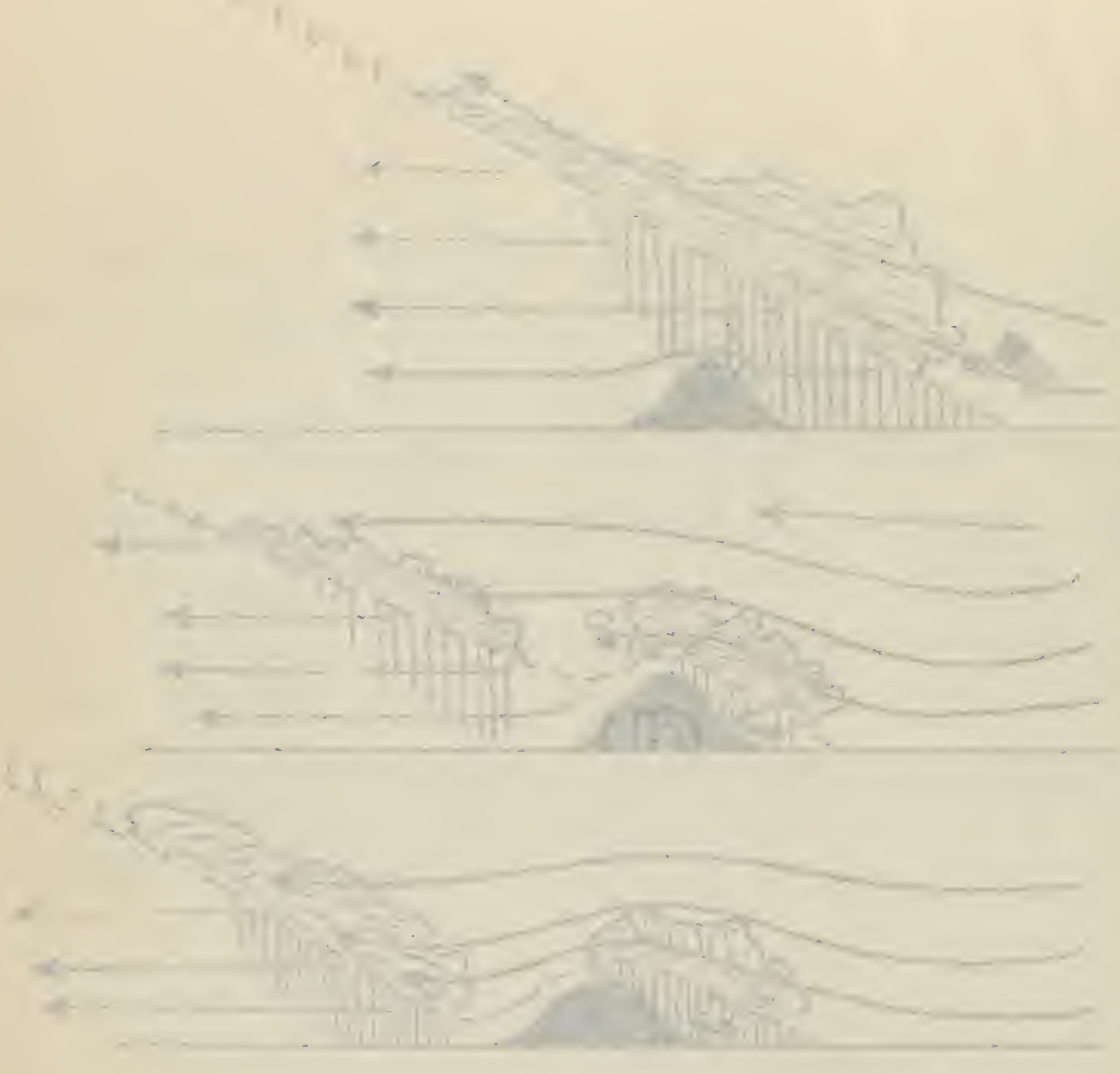
after J. Bjerknes

Figure 1



A warm front passing over a mountain ridge, after J. Bjerknes

Figure 2

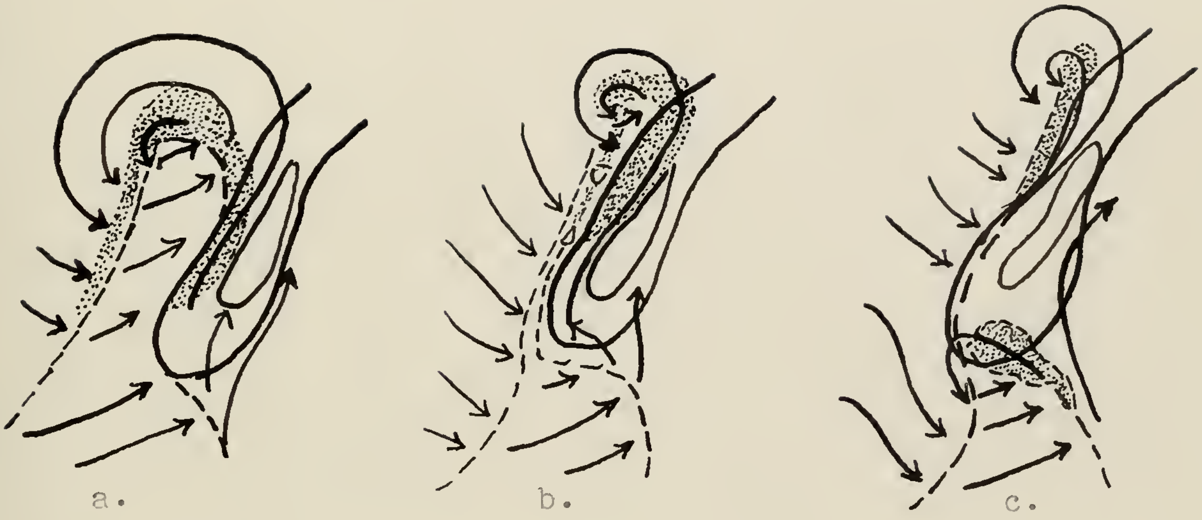


We frequently observe a similar phenomenon in the case of Polar Pacific air losing most of its moisture in its travel over Washington, Oregon, Idaho and Montana so that very little moisture remains when it has crossed the Rockies. However in cases when fresh Polar Continental air lies east of the Rockies (winter), then the Polar Pacific acts as a warm mass over the Polar Continental air and a blizzard condition results. After the air of Polar Pacific origin has stagnated over North Central U. S. for a day or two when it may form a cold wedge under a Tropical Gulf air mass, and warm front precipitation as rain or snow over the Northern Mississippi Valley States can result.

EFFECTS OF MOUNTAINS ON APPROACHING FRONTS.

The accompanying sketches (Figure 1) illustrate the effects of the approach of cold fronts making various angles with the face of a mountain. In cases (a) and (b) the fairly large pattern of pre-frontal precipitation is formed due to the component of the current in advance of the cold front which is normal to the mountain contours. In case (c) the flow is toward the narrow edge of the mountain and divergence results so that the only pre-frontal rain formed will be in a small area at the edge of the mountain and this precipitation merges with the cold front precipitation.

The effect of a mountain ridge on a warm front is illustrated by the accompanying sketches (Figure 2). A typical warm front whose slope is greatly exaggerated is shown approaching a mountain ridge. The mountain tends to regard the advance of the warm front. The lower stream lines in the air under the front being deflected upward by the mountain. When the frontal surface reaches the mountain ridge cold air is trapped against the ridge and only the upper portion of the warm front can get over the top of the ridge. The clouds dissipate in the downward current on the leeward side of the ridge and precipitation is confined to the windward side. Some distance beyond the ridge the upward currents are resumed and the frontal surface reforms with its characteristic cloud system and precipitation.



Formation of secondary cyclone due to damming effect of high mountain ranges,

after J. Bjerknes

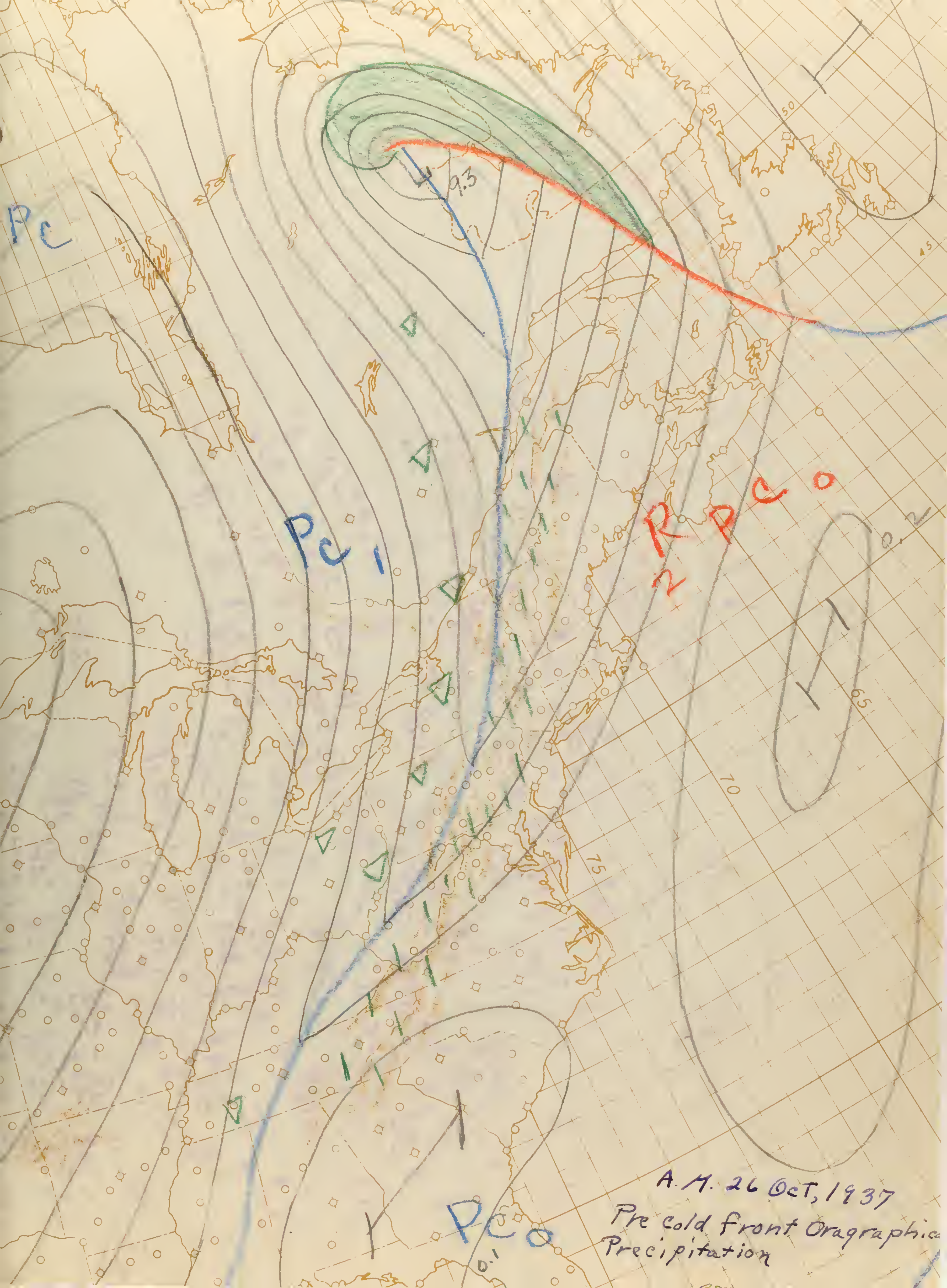
Figure 3

In some cases the cold wedge trapped on the windward side of the ridge is maintained with its clouds and precipitation for an abnormally long time and an excessive quantity of rainfall occurs. This was the situation causing the flood conditions in the Los Angeles region in January, 1935. A warm front with an open warm sector approached the coast and rain persisted on the west slopes of the coasted ranges until the warm sector was finally occluded by the arrival of a cold front and since the air behind the cold front was colder than the trapped wedge of cold air it replaced the cold wedge and stopped the precipitation.

Another effect of mountain ranges on approaching wave which is found occasionally at the southern end of the Allegheny Mountains is illustrated in the accompanying sketch (Figure 3). It illustrates the formation of a secondary cyclone by the bending of the southern part of the warm front to the northward around the mountain by the warm sector current. The northern part of the wave occludes against the mountain side and stagnates there while the southern part of the cold front together with the southern part of the warm front surface which can move freely around the end of the range form an open wave which moves off as a secondary system.

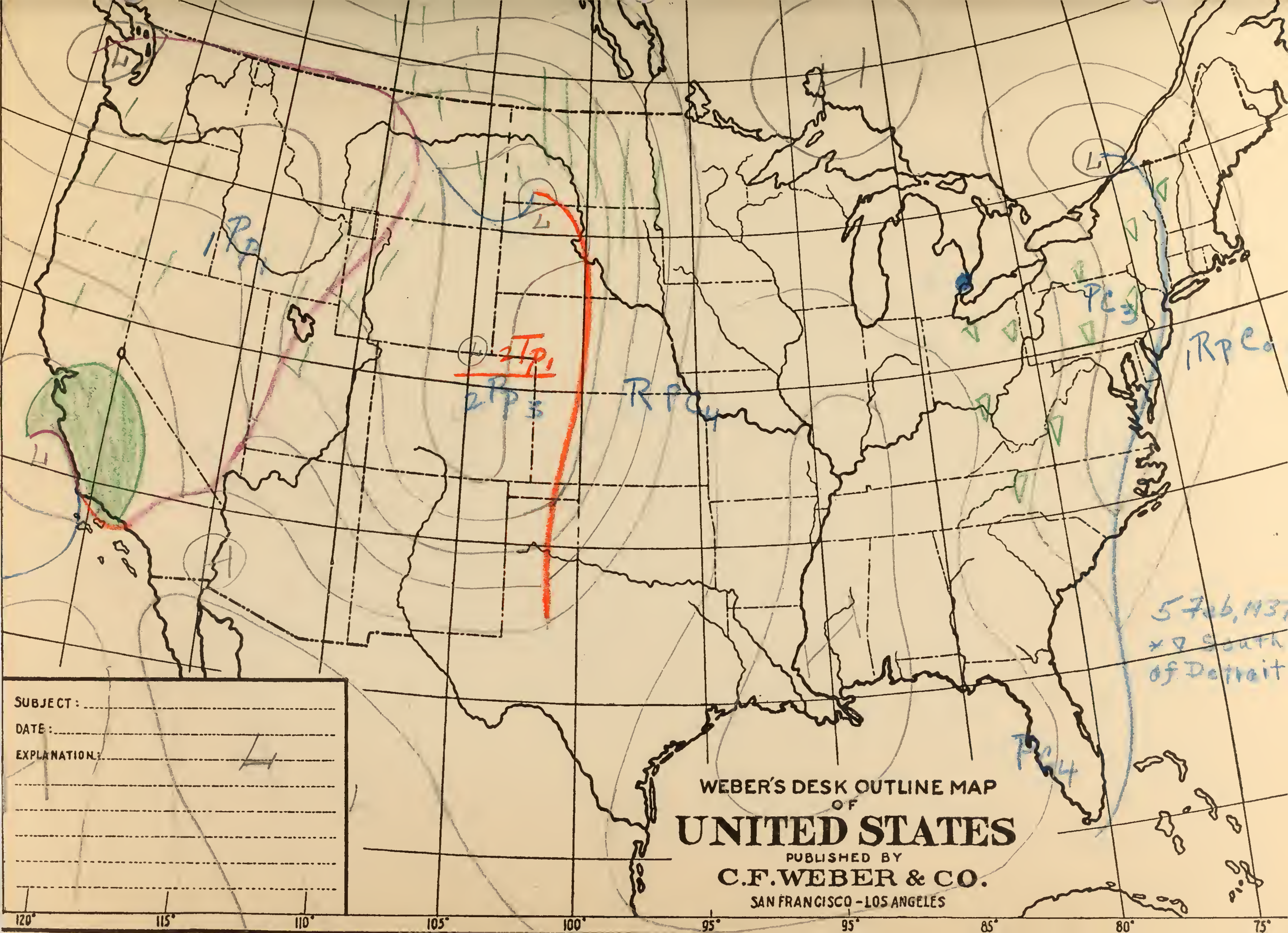
PRE-COLD FRONT OROGRAPHICAL PRECIPITATION.

The approach of a cold front to regions presenting orographical obstacles to the flow causes a change in wind direction and generally an increase in wind velocity. These changes are usually sufficient to change theweather completely even for a long distance ahead of the cold front. An example of this is the approach of a cold front to the California coast. This approach in many cases causes an onshore flow of maritime which has a component normal to the mountain slopes which causes the air to be forced up the mountain slopes. If this warm maritime air mass is fairly stable then fog or stratus clouds form and drizzle or light orographical precipitation may result. If the warm maritime air mass is fairly fresh Tropical Pacific air then instability showers or even thunderstorms



A.M. 26 Oct, 1937
Pre cold front Oragraphica
Precipitation

may result. Another example of pre-frontal orographical precipitation is that due to flow induced up the slopes of the Allegheny Mountains by the approach of a cold front from the west. The morning map for 26 October, 1937, shown on the following page illustrates this effect. In this case the warm air being forced aloft is fairly stable and only light, steady, orographical precipitation results. The precipitation is in the form of rain since temperatures are well above 32°F. in the warm air. The increase in the gradient of pressure caused by the approach of the front and the change in wind direction to south westerly aid in forcing the warm air up the mountain slopes sufficiently to cause precipitation.


WEBER'S DESK OUTLINE MAP
OF
UNITED STATES
PUBLISHED BY
C.F. WEBER & CO.
SAN FRANCISCO - LOS ANGELES
SUBJECT:
DATE:
EXPLANATION:
120°
115°
110°
105°
100°
95°
95°
85°
80°
75°
1Rp1
2Tp1
2Rp3
RPc4
Pc3
1RpCo
Pc4
L
L
L
L
L
H
5 Feb, 113
* ∇ South
of Detroit

TIME SOUNDING 0400 EST

COMPUTED BY

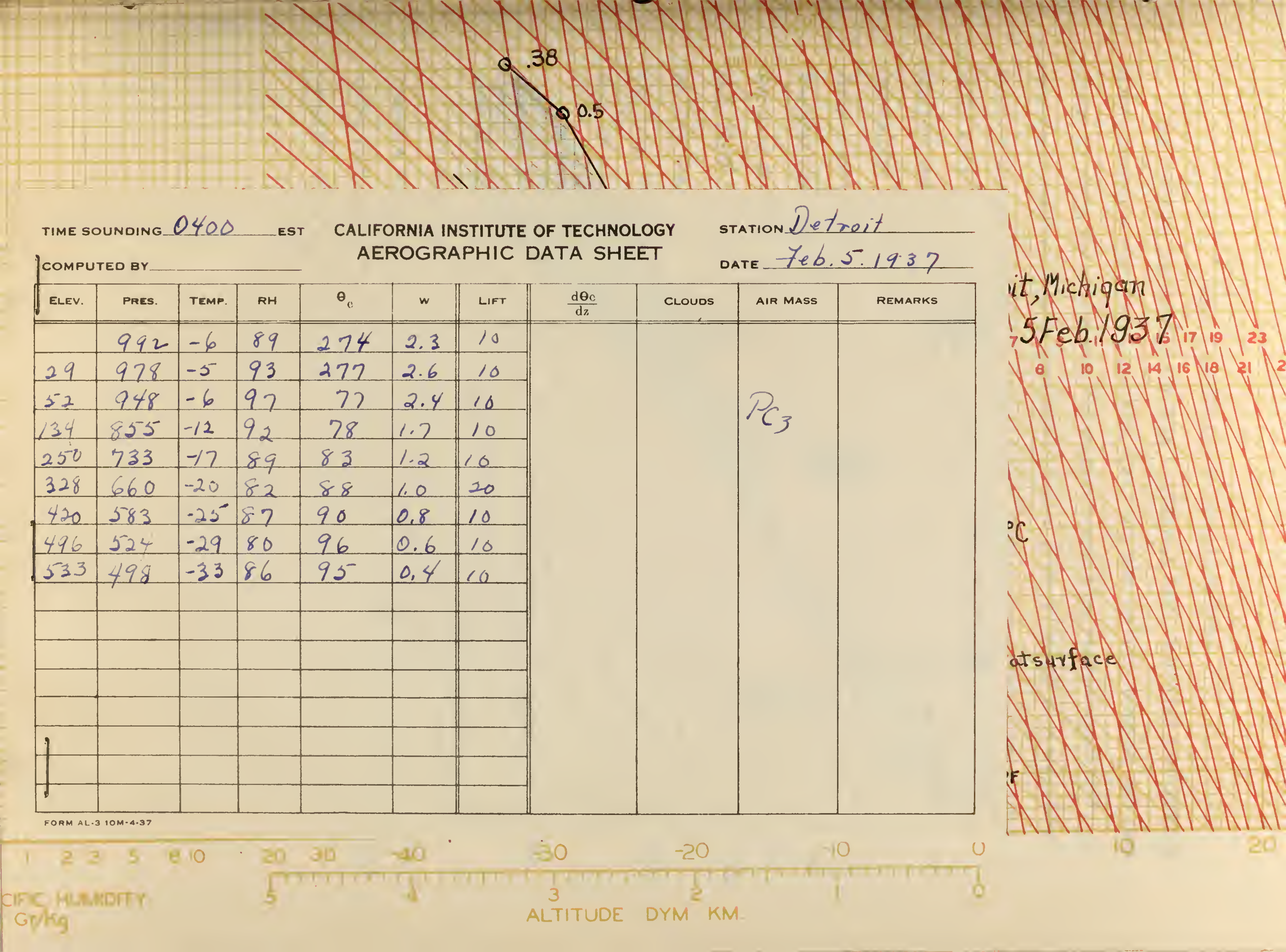
CALIFORNIA INSTITUTE OF TECHNOLOGY
AEROGRAPHIC DATA SHEET

STATION Detroit

DATE Feb. 5. 1937

ELEV.	PRES.	TEMP.	RH	θ_c	W	LIFT	$\frac{d\theta_c}{dz}$	CLOUDS	AIR MASS	REMARKS
	992	-6	89	274	2.3	10				
29	978	-5	93	277	2.6	10				
52	948	-6	97	77	2.4	10			Pc3	
134	855	-12	92	78	1.7	10				
250	733	-17	89	83	1.2	10				
328	660	-20	82	88	1.0	20				
420	583	-25	87	90	0.8	10				
496	524	-29	80	96	0.6	10				
533	498	-33	86	95	0.4	10				

FORM AL-3 10M-4-37

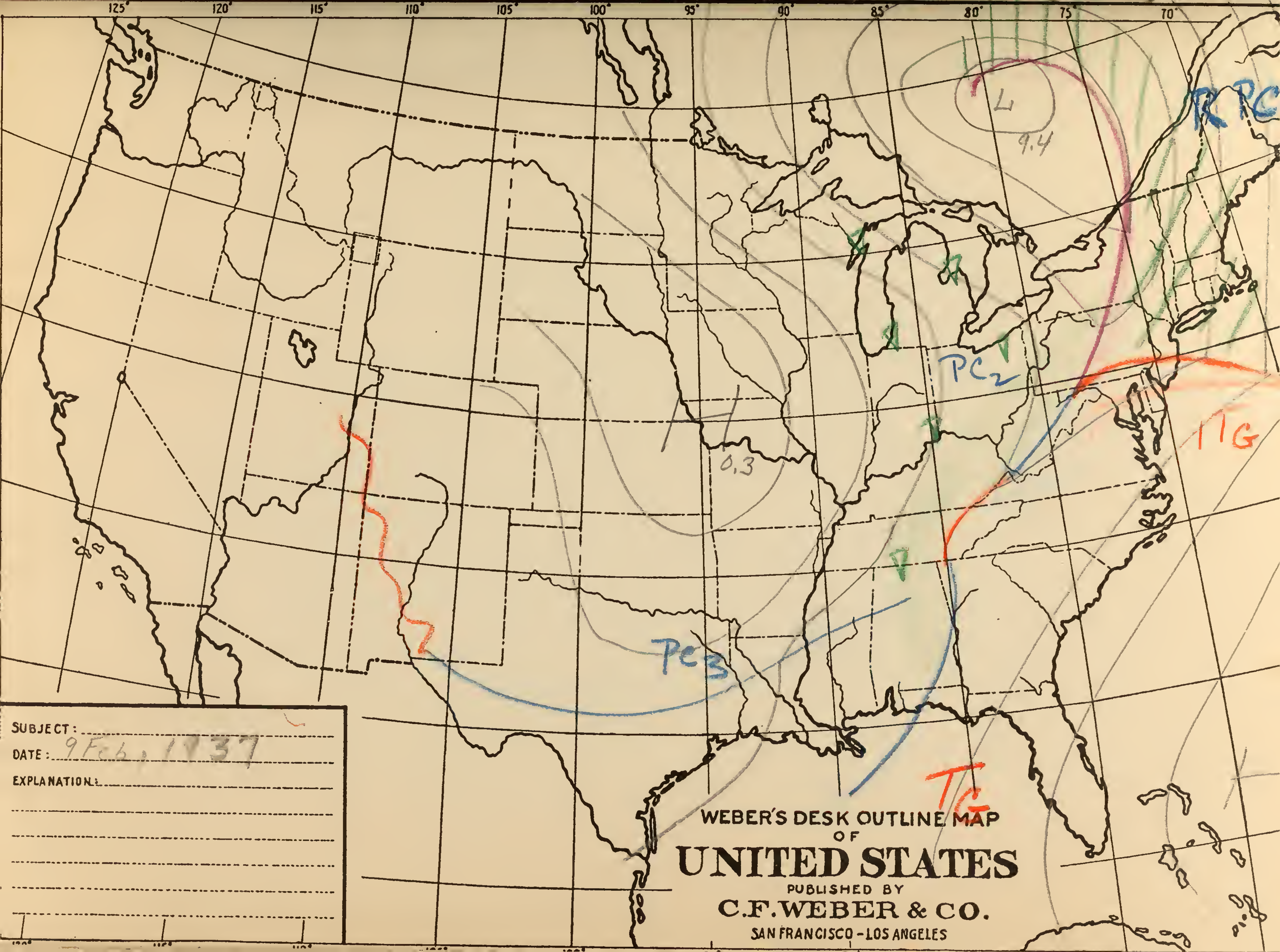


Snow Flurries Due To Surface Heating.

The sounding for Detroit for 0400 5 February, 1937, indicates that lifting cannot produce a significant positive area. Surface heating, however, can form clouds at about 700 meters when the surface temperature reaches about 28°F. A very small positive area is immediately formed which is topped by a very large negative area at about 1800 meters. If the surface temperature reaches about 31°F. the size of the positive area begins to be significant and light snow flurries could be experienced. Since the amount of surface heating likely to be experienced will produce only a relatively small positive area compared to the large negative area formed above it, cloud tops should remain comparatively low. The specific humidities are low and the velocities likely to occur (indicated by the size of the positive area) are comparatively small, the turbulence will be only light to moderate within the clouds, also the synoptic situation is changing so that the flow across the lakes and into the United States will not continue for long, therefore, precipitation should be as light snow flurries to the southeast of the lakes during the day, the amount of precipitation being small.

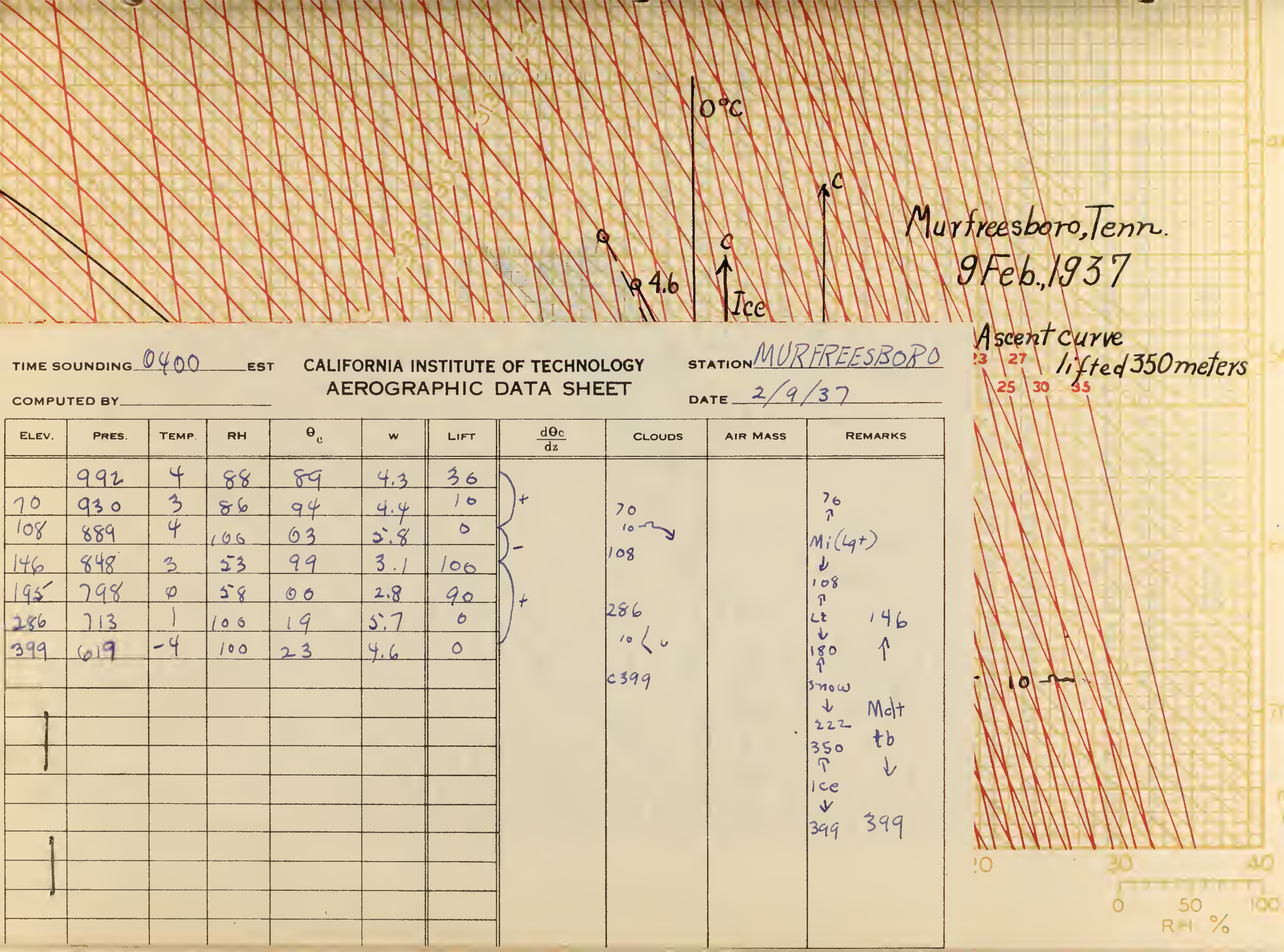
No precipitation occurred at Detroit but scattered light snow flurried occurred over a large region to leeward of the lakes where temperatures reached were higher, the precipitation amounting to only a few hundredths of an inch.

Divergence is occurring at Detroit and along the periphery of the high pressure area. The tendency at Detroit is t. 06. Divergence would tend to require that the surface temperature be higher than otherwise before a significant positive area could be formed.



SUBJECT:
DATE: 9 Feb, 1937
EXPLANATION:

WEBER'S DESK OUTLINE MAP
OF
UNITED STATES
PUBLISHED BY
C.F. WEBER & CO.
SAN FRANCISCO - LOS ANGELES


Murfreesboro, Tenn.
9 Feb., 1937

Ascent curve
lifted 350 meters

TIME SOUNDING 0400 EST

COMPUTED BY

CALIFORNIA INSTITUTE OF TECHNOLOGY
AEROGRAPHIC DATA SHEET

STATION MURFREESBORO

DATE 2/9/37

ELEV.	PRES.	TEMP.	RH	θ_c	W	LIFT	$\frac{d\theta_c}{dz}$	CLOUDS	AIR MASS	REMARKS
	992	4	88	89	4.3	36				
70	930	3	86	94	4.4	10	+	70		76 ↑
108	889	4	100	03	5.8	0	−	10 ⤵		Mi(4g+)
146	848	3	53	99	3.1	100		108		↓
195	798	0	58	00	2.8	90	+			108 ↑
286	713	1	100	19	5.7	0		286		Lt 146
399	619	−4	100	23	4.6	0		10 ⟨ ∪		↓ ↑ 180
								c399		↑ snow
										↓ Melt
										222 tb
										350 ↓ ↑
										Ice ↓
										399 399

Warm Front Precipitation --- Rain ---

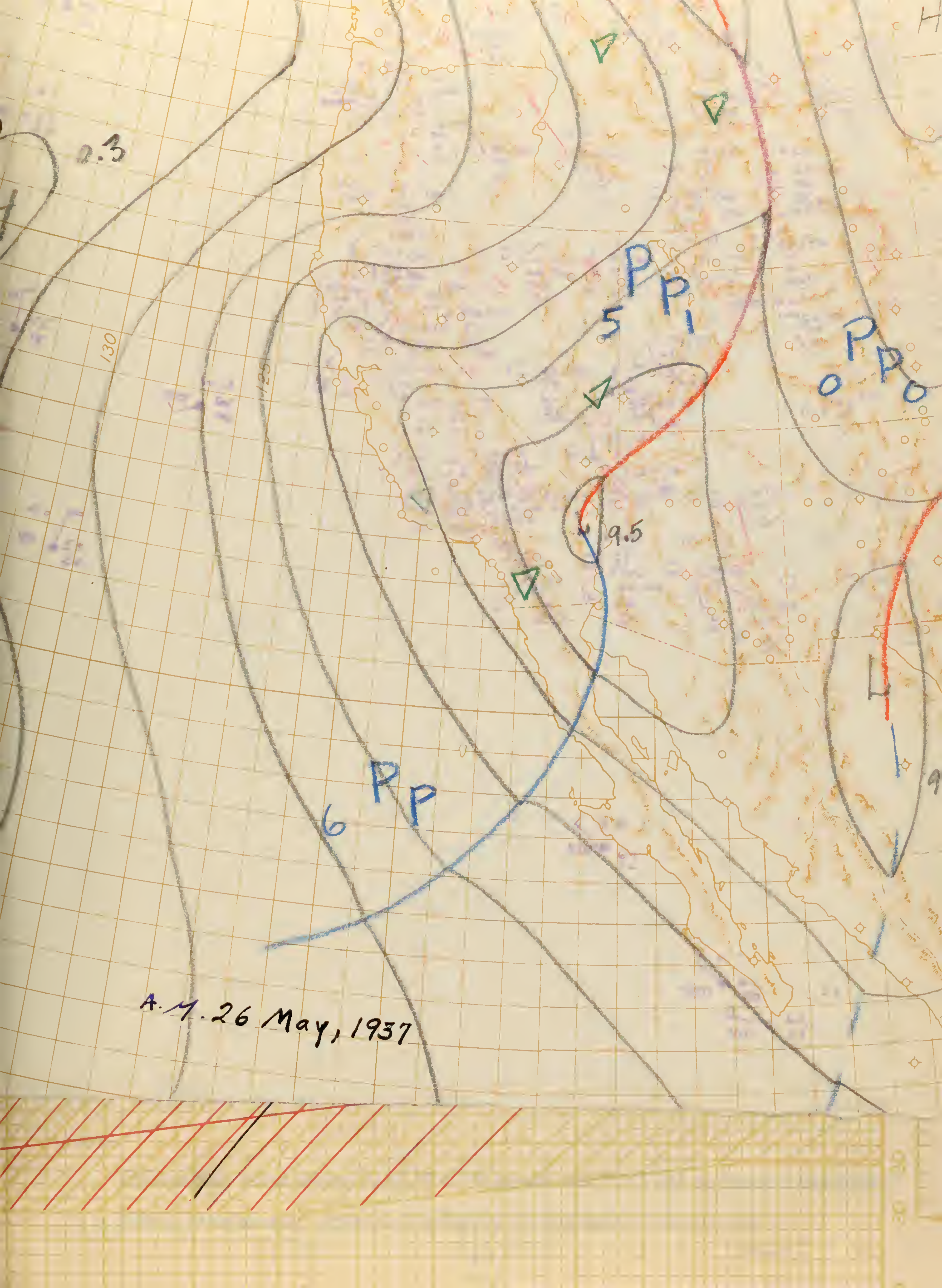
The weather map for 9 February, 1937, shows Murfreesboro, Tenn., on the outer fringes of the effects of over-running of TG_1 air over a wave on a front to the East.

The 0400 sounding for 9 February, 1937, for Murfreesboro, Tenn., shows that up to the limit of the sounding, ie, up to 3990 meters no positive area exists and that if the cold air under the front is lifted 350 meters by orographical means then a small positive area is formed which contains the ice crystal level. Above this positive area an extra large negative area would be formed thus insuring that only light rain or snow or both could occur.

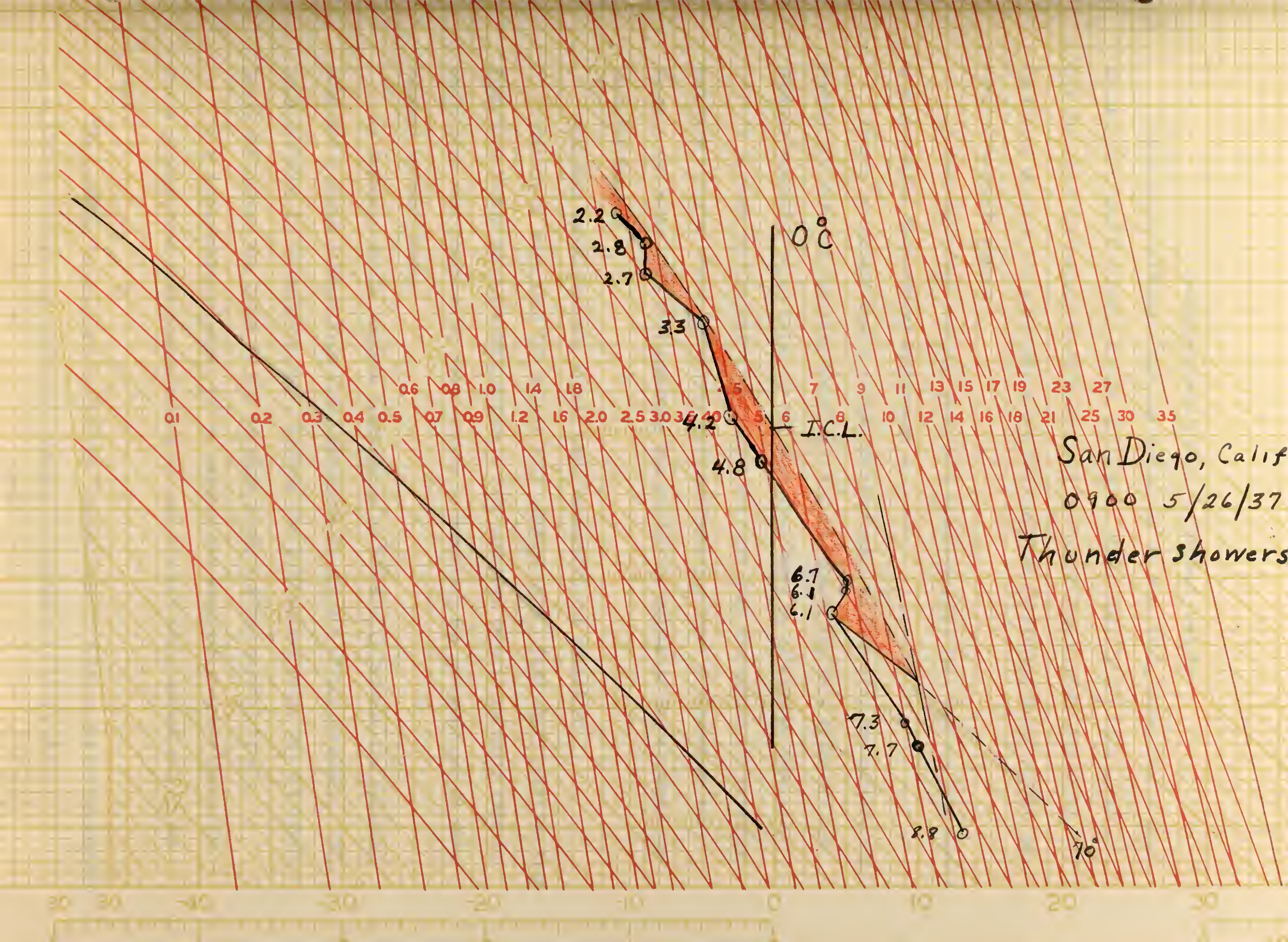
The sounding does not extend high enough to obtain any idea about the structure of the air over-running the warm front of the wave except that the positive lapse rate of equivalent potential temperature indicated for the upper layer indicates that that layer is stable.

At the time of the sounding an alto-stratus overcast was present. Ice, snow, light rain and mist were indicated for layers respectively as follows, above 3990 to 3500 meters, 2220 to 1800 meters, 1800 to 1080 meters and 1080 to 700 meters, but no precipitation is reaching the ground at the time of the sounding. This is due to evaporation of the precipitation before reaching the ground.

Shortly after the sounding was made a light and fairly steady rain occurred at Murfreesboro.



A.M. 26 May, 1937



San Diego, Calif
0900 5/26/37
Thunder Showers

Thundershowers Caused By Surface Heating.

The synoptic situation for the morning of 26 May, 1937, shows that a cold front has passed San Diego during the night. Polar Pacific air with about a six day ocean trajectory is flowing along the coast from a north direction. Scattered showers are occurring along the Southern California Coast and in the Coastal mountain ranges.

An 0900 San Diego sounding reports 9 strato-cumulus from 1040 to 1580 meters, 9 alto cumulus from 2160 to 2650 meters .

It can be assumed that a column of air forced to rise from the surface will retain its value of specific humidity. We, therefore, use this value and are further justified in so doing by the fact that there is no surface inversion.

It is seen that relative humidities are very high throughout the sounding and that lifts of about 100 meters will saturate the lower 3 kilometers and about a 400 meter lift will saturate the air to the height of the sounding and probably beyond.

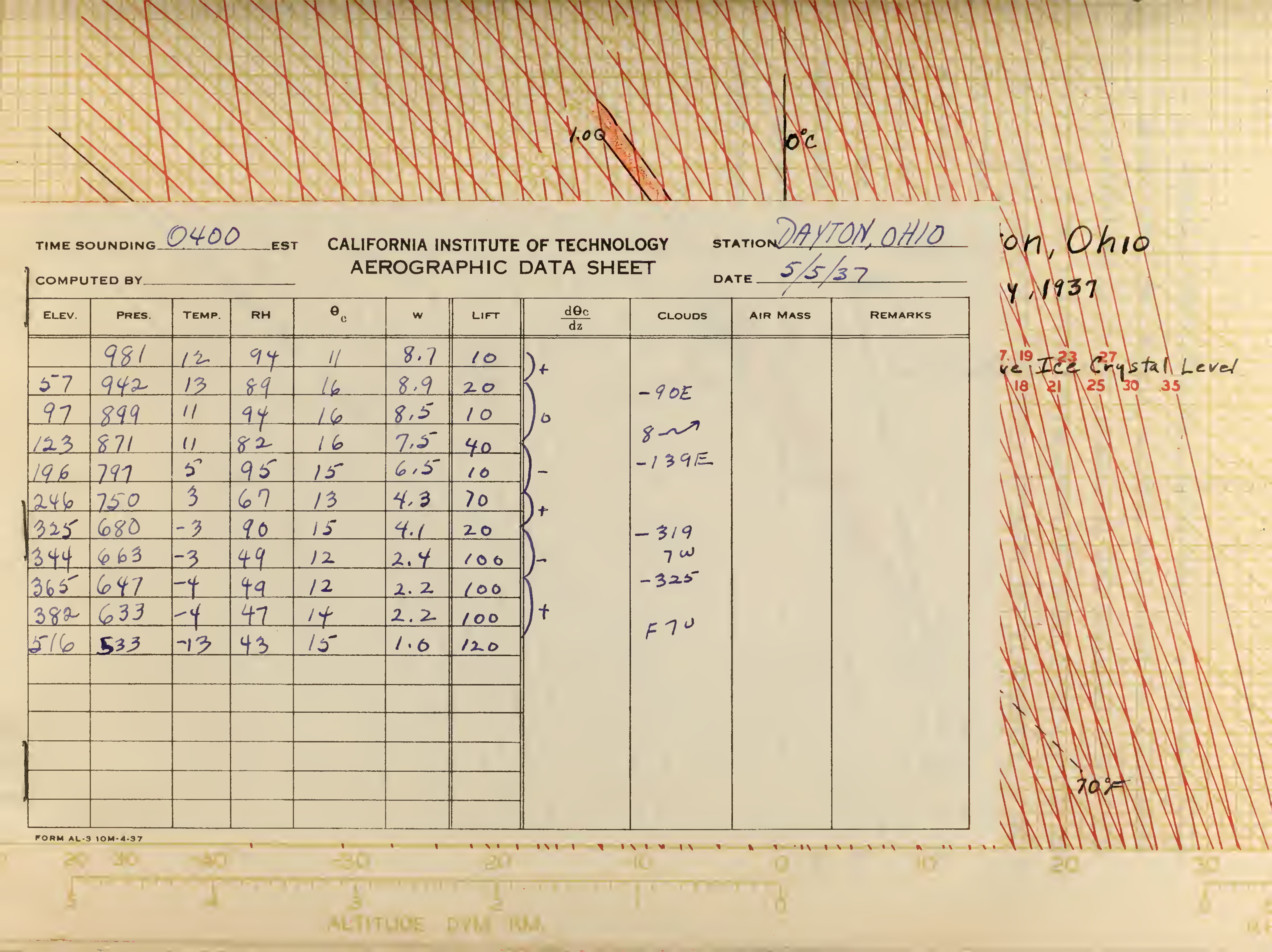
Specific humidities are fairly high throughout the soundings.

Lifting of less than 100 meters will produce only a very small positive area from 1880 meters to about 3200 meters. This positive area is so small that it could have been produced by minor errors in computing the sounding and is considered insignificant.

An increase in the surface temperature to 70° F will produce the positive area shown which extends from 1200 kilometers to the top of the sounding. This positive area is of moderate size, extends for 1800 meters below the ice crystal level and beyond the limit of the sounding above the ice crystal level.

If a temperature of about 70° is reached the conditions appear favorable for a thunderstorm with precipitation as rain but not quite severe enough for hail.

The maximum temperature reached by Pasadena was 70°F and a shower accompanied by a little thunder and lightening occurred in Pasadena at about 1630.



TIME SOUNDING 0400 EST

COMPUTED BY

CALIFORNIA INSTITUTE OF TECHNOLOGY
AEROGRAPHIC DATA SHEET

STATION DAYTON, OHIO

DATE 5/5/37

ELEV.	PRES.	TEMP.	RH	θ_c	w	LIFT	$\frac{d\theta c}{dz}$	CLOUDS	AIR MASS	REMARKS
	981	12	94	11	8.7	10	+			
57	942	13	89	16	8.9	20		-90E		
97	899	11	94	16	8.5	10	0			
123	871	11	82	16	7.5	40		8 ↗		
196	797	5	95	15	6.5	10	-	-139E		
246	750	3	67	13	4.3	70	+			
325	680	-3	90	15	4.1	20		-319		
344	663	-3	49	12	2.4	100	-	7ω		
365	647	-4	49	12	2.2	100		-325		
382	633	-4	47	14	2.2	100	+	F7ᵘ		
516	533	-13	43	15	1.0	120				

FORM AL-3 10M-4-37

Example of thunderstorm due to surface heating - precipitation as rain.

The 0400 5 May, 1937, sounding at Dayton, Ohio, is taken as representative of the old Polar Pacific air mass occupying the upper Mississippi Valley. This sounding shows that if surface heating reaches 70°F then a positive area is formed which extends from about 1-½ kilometers upward for over 3-½ kilometers. A fairly large portion of the positive area lies below the ice crystal level so that velocities greater than 8 meters per second would probably be reached at the ice crystal level. The positive area decreases rather rapidly above the ice crystal level so that although a thunderstorm would be expected when surface temperature reached about 70°F the precipitation should be as rain and not as any form of hail.

Scattered convective thunderstorms occurred in the Upper Mississippi where surface temperatures exceeded about 70°F.

Oakland, Calif.
400 25 Feb. 1937

nt Curve lifted
00 meters

TIME SOUNDING 0400 EST

COMPUTED BY

CALIFORNIA INSTITUTE OF TECHNOLOGY
AERОGRAPHIC DATA SHEET

STATION OAKLAND

DATE 2/25/37

ELEV.	PRES.	TEMP.	RH	θ_c	W	LIFT	$\frac{d\theta c}{dz}$	CLOUDS	AIR MASS	REMARKS
	1009	7	87	95	5.5	20	-	47		0
47	952	3	100	94	5.1	0		7—		Lt
77	917	1	100	94	4.6	0	0	77		Rain
92	900	0	100	94	4.4	0		92		N 145 145 N
221	764	-3	100	04	4.0	0	+	10~—		Ice
299	693	-5	100	09	3.8	0		221		15 9 E

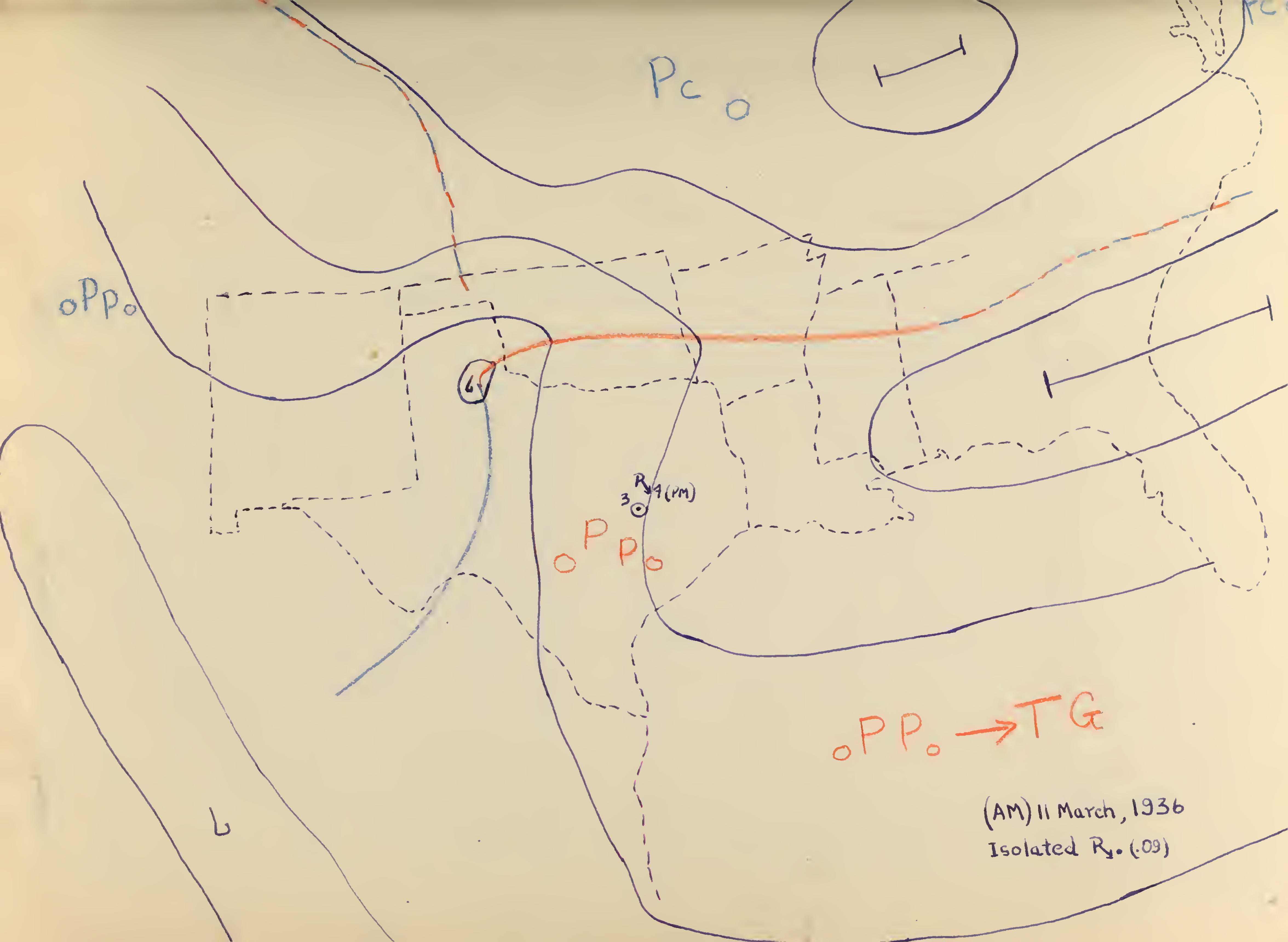
FORM AL-3 10M-4-37

Shower type precipitation due to orographical lifting.

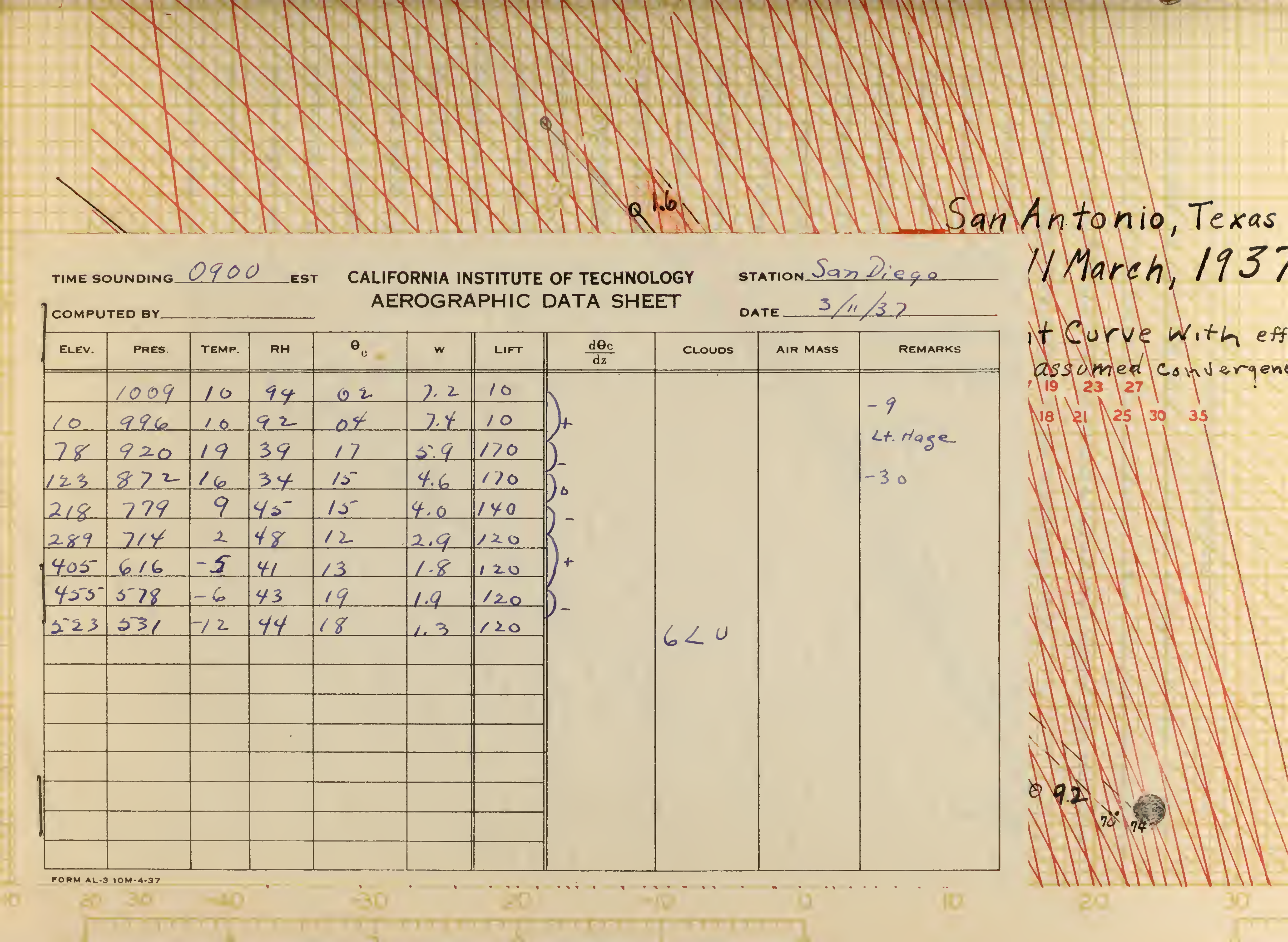
The morning map for 25 February, 1937, shows scattered shower type precipitation occurring in the fairly fresh Polar Pacific air flowing over Northern California and part of Southern California. The precipitation is in the form of light rain at Oakland, in rain showers at stations of moderate elevation to the South, changing to snow showers in the mountains and in the vicinity of them.

The sounding for Oakland shows light rain at Oakland extending from 1450 meters to the surface. The surface point is not yet saturated since the rain has just started. All points from 470 meters up are saturated. The adiabatic chart shows that if the air at Oakland is lifted 200 meters to saturate the surface point then a small positive area is formed which extends slightly beyond the ice crystal level. Above the small positive area lies a large negative area starting at about 1100 meters. The lifted curve with the positive and negative areas closely resembles the typical setup for shower type rain, but no thunderstorm.

An increase of surface temperature of 7.4°F will produce a slightly larger positive area than in case of the assumed lift of 200 meters. The showers which occurred were probably largely due to surface heating.



(AM) 11 March, 1936
Isolated R_y. (.09)



San Antonio, Texas
11 March, 1937
t Curve with eff
assumed convergen

TIME SOUNDING 0900 EST

COMPUTED BY

CALIFORNIA INSTITUTE OF TECHNOLOGY
AEROGRAPHIC DATA SHEET

STATION San Diego

DATE 3/11/37

ELEV.	PRES.	TEMP.	RH	θ_c	W	LIFT	$\frac{d\theta c}{dz}$	CLOUDS	AIR MASS	REMARKS
	1009	10	94	02	7.2	10				
10	996	10	92	04	7.4	10	+			-9
78	920	19	39	17	5.9	170	-			Lt. Haze
123	872	16	34	15	4.6	170	0			-30
218	779	9	45	15	4.0	140	-			
289	714	2	48	12	2.9	120				
405	616	-5	41	13	1.8	120	+			
455	578	-6	43	19	1.9	120	-			
523	531	-12	44	18	1.3	120		6∠U		

FORM AL-3 10M-4-37

Isolated Thunderstorm.

From 1500 to 1600 on 11 March, 1937, a mild thunderstorm with .09 inch precipitation as rain occurred at San Antonio, Texas. No other thunderstorms were reported within about 300 miles and no front came closer than 200 miles. The maximum temperature reached at San Antonio was 68°F.

The morning weather map shows that an old Polar Pacific air mass approaching the properties of Tropical Gulf air lies over the Central and Eastern part of Texas. A 29.80 low is located Southeast of Amarillo and a slow moving cold front lies in West Central Texas. Some convergence is occurring as indicated by the -.02 tendency at San Antonio when the normal diurnal tendency is +.01.

The sounding shows that the air is stratified as to moisture content. From 1150 to 1172 meters an 8° per kilometer lapse rate of equivalent potential temperature exists, from 1720 to 2990 metera a 3° per kilometer lapse rate and from 3860 to 4920 meters a 2° per kilometer lapse rate of equivalent potential temperature exists.

The maximum temperature reported by San Antonio for the day was 68°F (20°) which would be insufficient to allow the convective condensation level to be reached if the curve remained unaltered during the day. But convergence will change the curve greatly due to the large lapse rate of specific humidity from the 1720 to the 2990 meter level. Theeffects of 20 percent convergence are shown in the pencil curve to the left of the ascent curve. It is seen that the convergence assumed would straighten out the ascent curve and enable convection to start from the 1150 meter level since a positive area is formed above this level by the effect of the convergence. The amount of convergence assumed is probably excessive for this case, but any convergence whatever will tend to enable a positive area (suffieient to produce a thunderstorm) to be formed more easily.

Some of the ways in which sufficient positive area so situated as to cause a thunderstorm with precipitation as rain are:-

1. Action of 20 percent convergence.

2. No convergence, but surface temperature of $73\frac{1}{2}^{o}F$.

3. 16% convergence and temperature of $72^{o}F$.

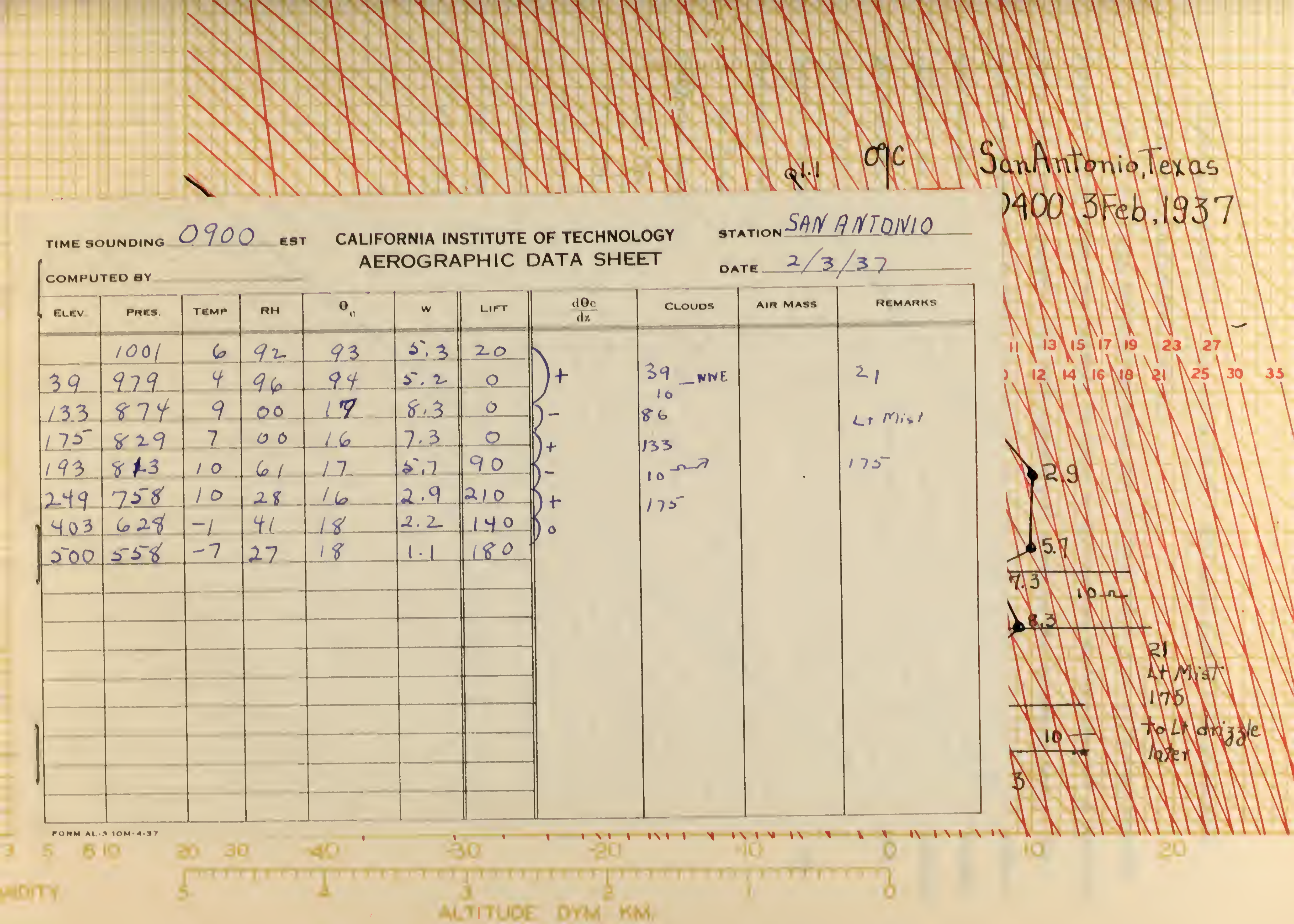
4. No convergence, but a lift of 450 meters will move the 2990 meter point dry adiabatically upward enough to clear the moist adiabatic curve along which free convection from the 1150 meter level is proceeding and to thus allow a positive area to be formed which will be situated so as to favor a thunderstorm with precipitation as rain.

5. The value used for the surface specific humidity is 9.0 grams per kilogram. If this value were actually larger then the temperature required would be less.

In this case it is difficult to tell just what caused this isolated thunderstorm, however, it seems probable the combined effects of some convergence, and some lifting coupled with a surface temperature near San Antonio which was somewhat higher than the 68^{o} maximum reported there.

q1.1 09C San Antonio, Texas

400 3Feb,1937



TIME SOUNDING 0900 EST

COMPUTED BY

CALIFORNIA INSTITUTE OF TECHNOLOGY
AEROGRAPHIC DATA SHEET

STATION SAN ANTONIO

DATE 2/3/37

ELEV.	PRES.	TEMP	RH	θ_e	W	LIFT	$\frac{d\theta_e}{dz}$	CLOUDS	AIR MASS	REMARKS
	1001	6	92	93	5.3	20				
39	979	4	96	94	5.2	0	+	39 _NNE 10		21
133	874	9	00	17	8.3	0	–	86		Lt Mist
175	829	7	00	16	7.3	0	+	133		
193	813	10	61	17	5.7	90	–	10 ↗		175
249	758	10	28	16	2.9	210	+	175		
403	628	-1	41	18	2.2	140	0			
500	558	-7	27	18	1.1	180				

FORM AL-3 10M-4-37

Stable precipitation - mist and drizzle - resulting partly from convergence and partly from orographical lifting.

A misty and light drizzle condition for the Gulf Coast part of Texas extending inland slightly beyond San Antonio is shown on the morning weather map for 3 February, 1937, shown after page 41. The 0400 sounding is shown on the following page. The third point from the surface was omitted from the sounding report, but it is evident that the lapse rate within the stratus layer will be practically along the saturated adiabatic so that the third point is known since the top of the stratus was reported. The sounding shows that no precipitation is reaching the surface as yet but light mist is falling from 1750 to 210 meters, ie, from the top of the strato-cumulus layer. The region below 210 meters became saturated from the falling mist and the mist soon changed to light drizzle.

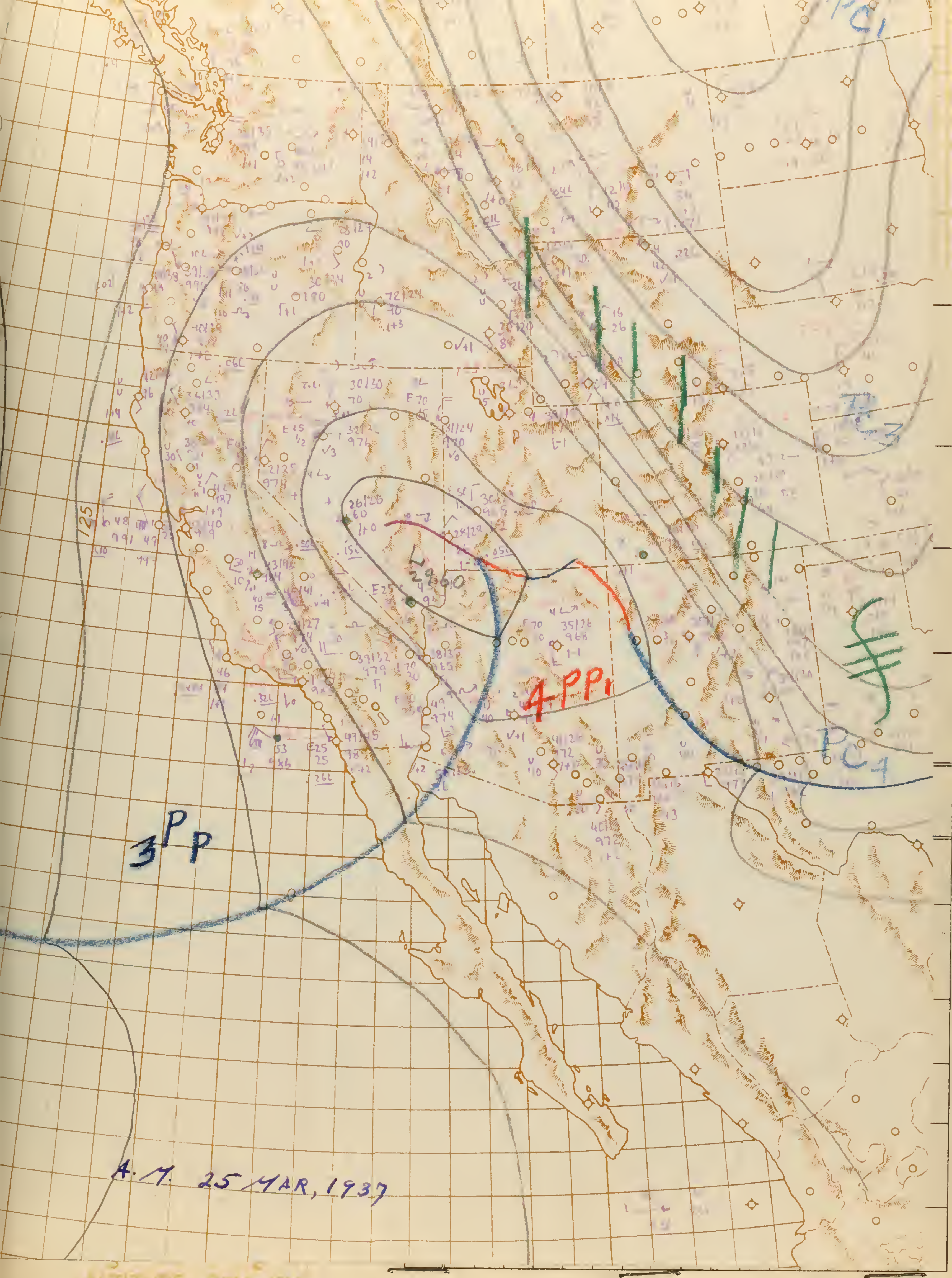
The factors causing the stratus and strato-cumulus overcast conditions in Southeast Texas are:

(a) The surface wet by warm front rain on 1 February.

(b) The air reaching Texas has had some Gulf trajectory.

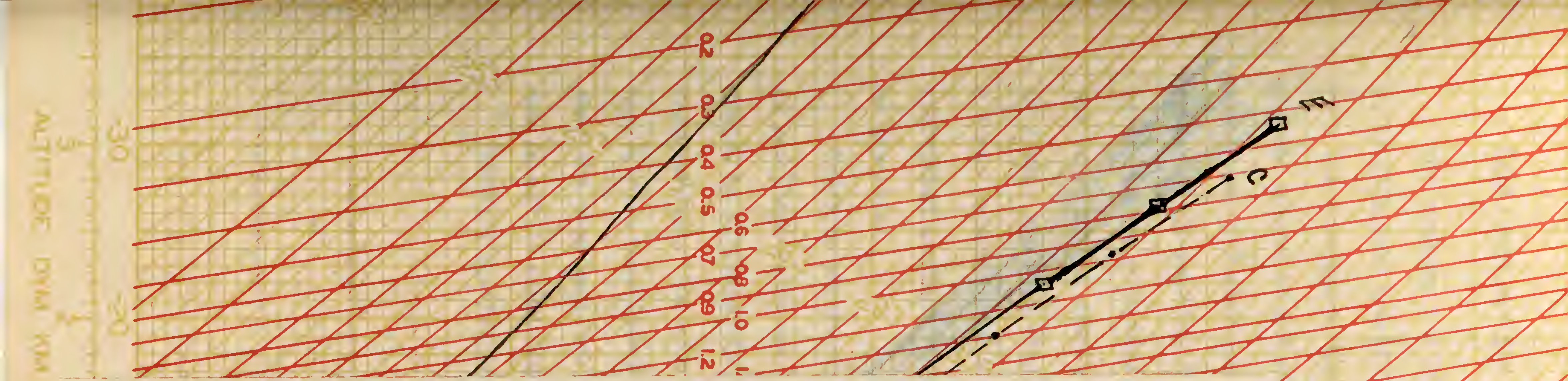
(c) An active inflow of air from over the Gulf was induced by a region of cyclogenesis in Western Texas, the Pan Handle, and Eastern New Mexico.

(d) Some orographical lifting and some convergence caused by the presence of a small isallobaric low on 3 February.



A.M. 25 MAR, 1937

ALTITUDE DYM KM.



TIME SOUNDING 0900 EST

COMPUTED BY

CALIFORNIA INSTITUTE OF TECHNOLOGY
AEROGRAPHIC DATA SHEET

STATION SANDIEGO, CALIF.

DATE 3/24/37

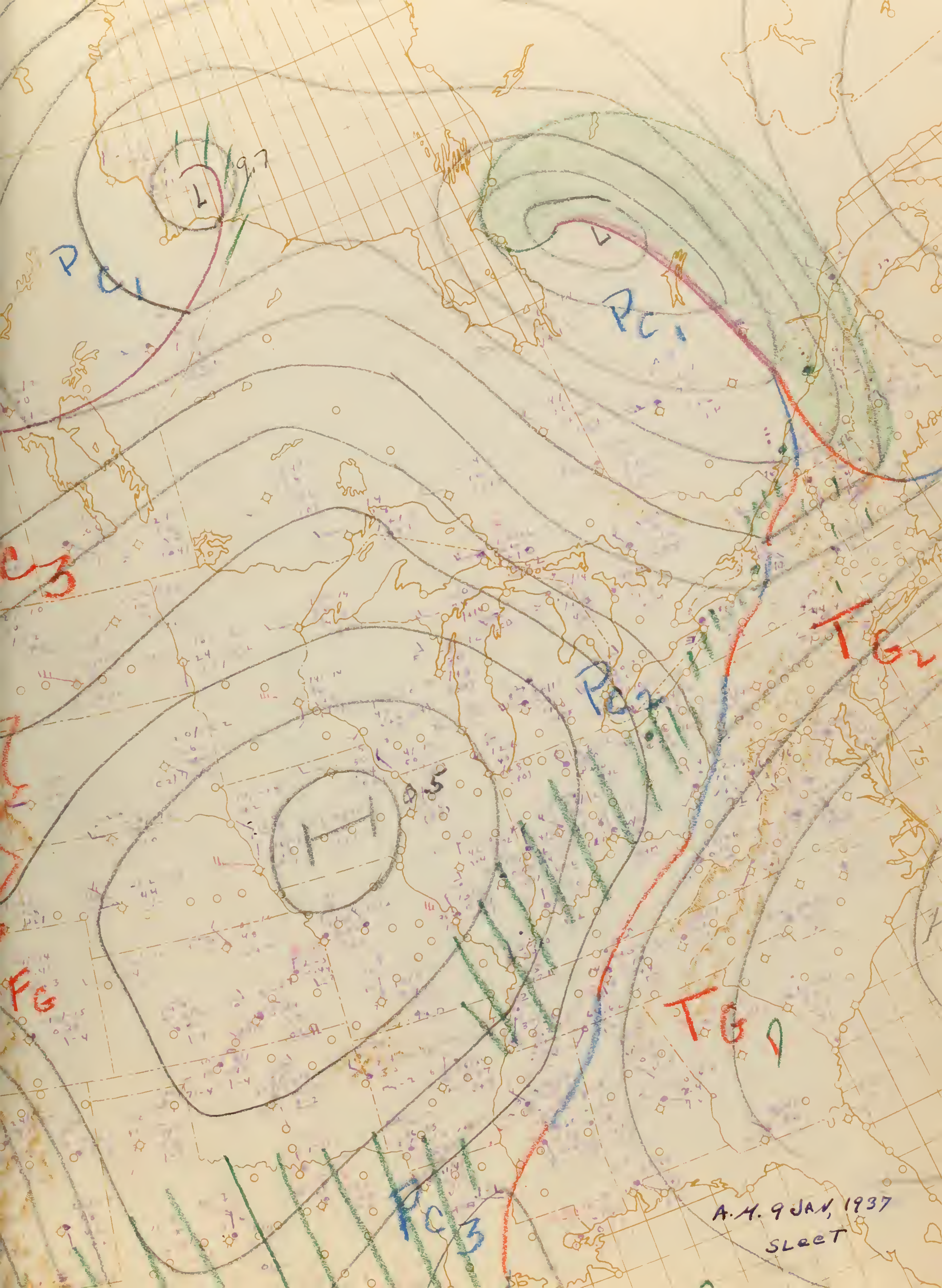
ELEV.	PRES.	TEMP.	RH	θ_c	w	LIFT	$\frac{d\theta c}{dz}$	CLOUDS	AIR MASS	REMARKS
	1015	8	82	96	5.9	20	0			
19	991	7	82	96	5.2	40	+	−E67		
41	964	7	81	98	5.3	40	0	3~		
72	927	5	86	98	4.9	30		−E85		
98	900	3	84	98	4.5	30	−			
137	857	−1	89	95	3.8	10	+			
166	826	2	69	01	3.7	60				
251	744	−1	44	02	2.1	120		−119		
395	620	−9	35	06	1.2	130		7~		−140
454	575	−13	44	08	1.0	120		140		Lt. Hage
513	532	−15	44	12	0.9	120				
								12		

Cold front passage -- lifted warm air remaining stable.

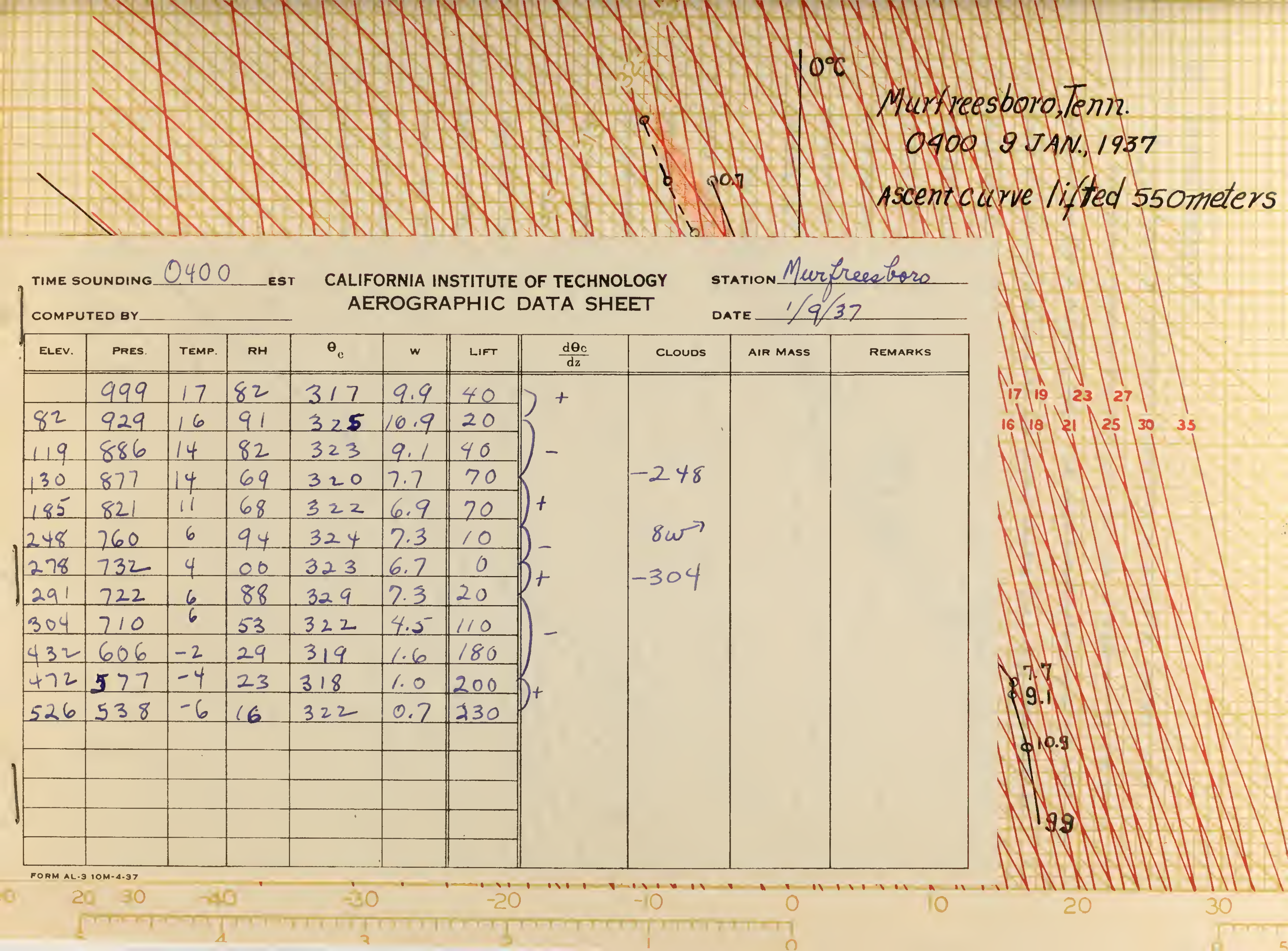
The sounding for 24 March, 1937, (San Diego) is taken in air which is soon to be lifted by a cold front. In order to determine the effect of lifting combined with the convergence normally present near the center of a cyclone, curves representing the effect of 20% convergence (curve CD) and the effect of 300 meters lift combined with 20% convergence (curve EF) are drawn. The lapse rate of equivalent Potential is negative from the 980 to the 1370 meter level and as soon as this layer becomes saturated convection will start along the moist adiabatic. Using the curve EF for combined 300 meter lift and 20% convergence a small positive area is formed which is almost entirely above the lifting ice crystal level. There is a large negative area encountered by the rising particle which will soon cause the convection to cease so that no thunderstorm or showery type of precipitation would be expected.

Moderate pre-frontal and frontal rain of a fairly steady type would be expected at San Diego since air containing a specific humidity of several grams will be forced up sufficiently to reach the lifting ice crystal level after saturation has been reached. The size of the positive area below the lifted ice crystal level is negligible, therefore no thunderstorm could occur. This is interesting in view of the fact that just two days previous a thunderstorm with soft hail occurred. In the meanwhile subsidence has greatly stabilized the air.

Moderate pre-frontal rain and a fairly steady rain of short duration occurred.



A.M. 9 JAN, 1937
SLEET



Murfreesboro, Tenn.
0400 9 JAN., 1937
Ascent curve lifted 550 meters

TIME SOUNDING 0400 EST

COMPUTED BY

CALIFORNIA INSTITUTE OF TECHNOLOGY
AEROGRAPHIC DATA SHEET

STATION Murfreesboro

DATE 1/9/37

ELEV.	PRES.	TEMP.	RH	θ_c	W	LIFT	$\frac{d\theta_c}{dz}$	CLOUDS	AIR MASS	REMARKS
	999	17	82	317	9.9	40	+			
82	929	16	91	325	10.9	20				
119	886	14	82	323	9.1	40	−			
130	877	14	69	320	7.7	70		−248		
185	821	11	68	322	6.9	70	+			
248	760	6	94	324	7.3	10	−	8w		
278	732	4	00	323	6.7	0	+	−304		
291	722	6	88	329	7.3	20				
304	710	6	53	322	4.5	110	−			
432	606	−2	29	319	1.6	180				
472	577	−4	23	318	1.0	200	+			
526	538	−6	16	322	0.7	230				

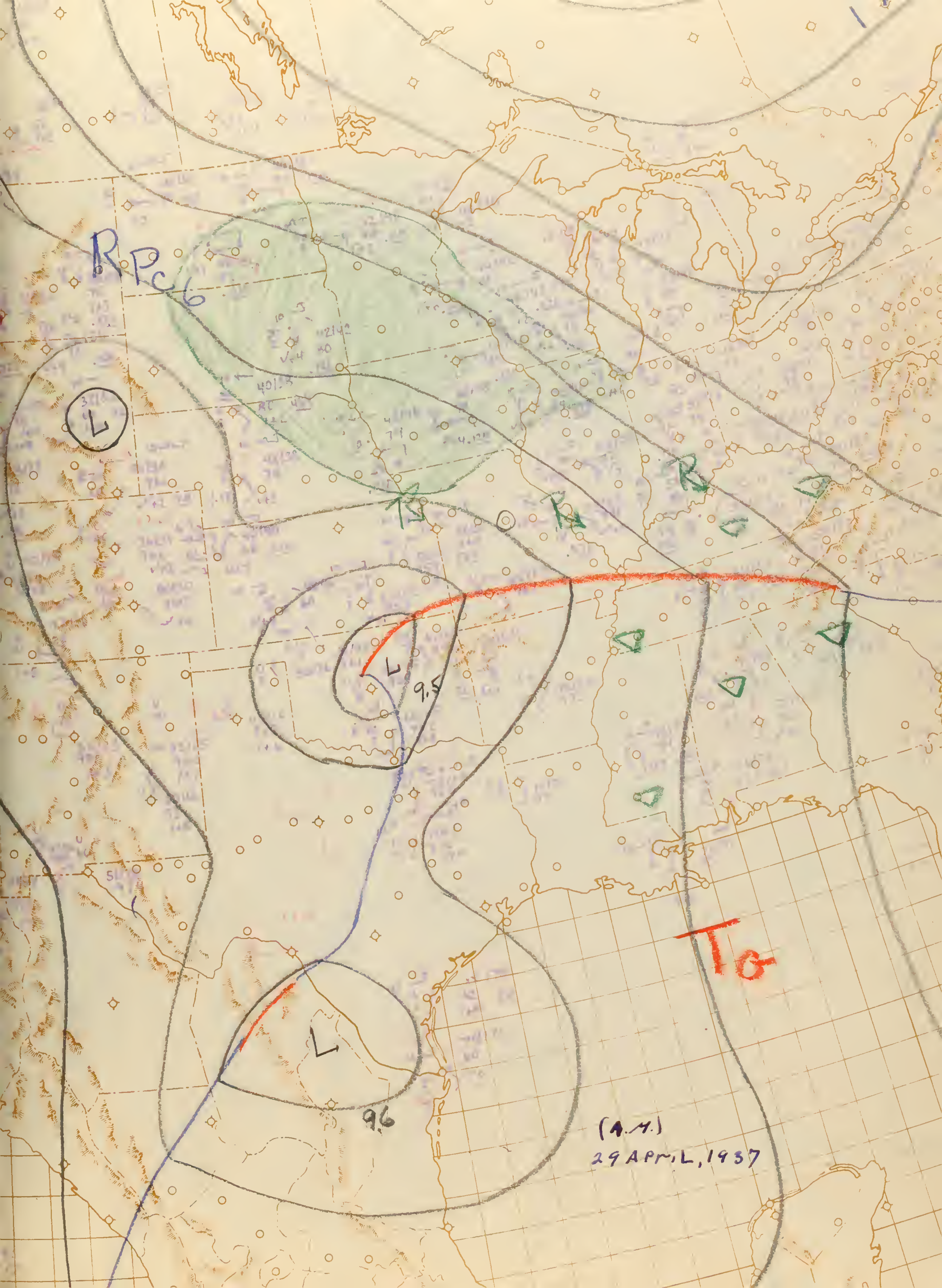
FORM AL-3 10M-4-37

II Frontal Conditions.

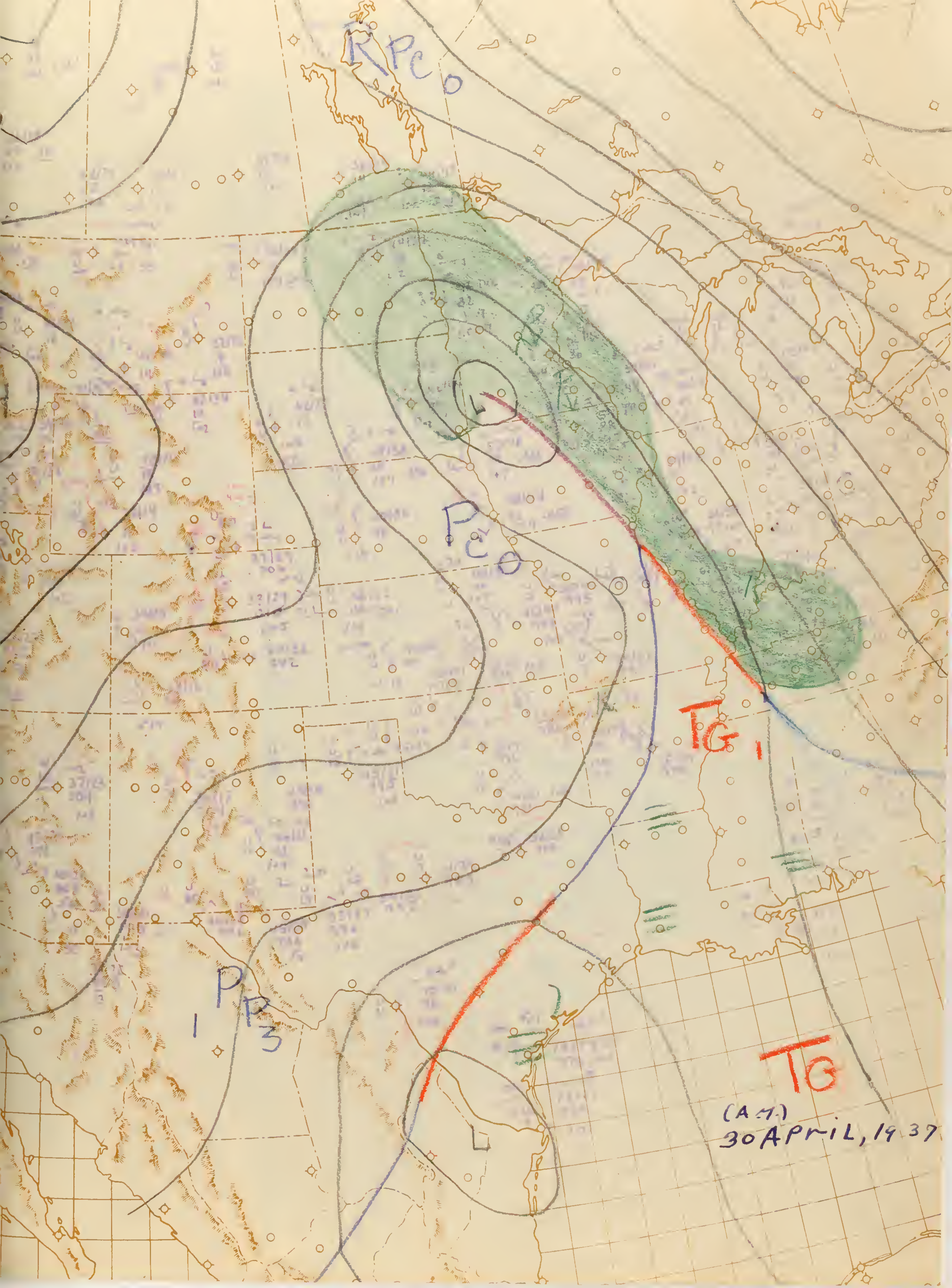
(b) Warm front or cold front precipitation involving instable air.

Conditions favoring the fall of sleet are illustrated by the A. M. Weather map for 9 January, 1937. In this caseTropical Gulf air with two days of land trajectory from its source region (ie, TG_2) with surface temperatures from 55° to 70° generally is overrunning Polar Continental air with two days land trajectory (ie, PC_2) which has surface temperatures of from 10° to 20°F under the region marking about the limit of the TG_2 over-running. The anticyclonic circulation in the TG_2 air and the orientation of the front nearly along the stream lines limit the TG_2 over-running to a rather short distance from the front.

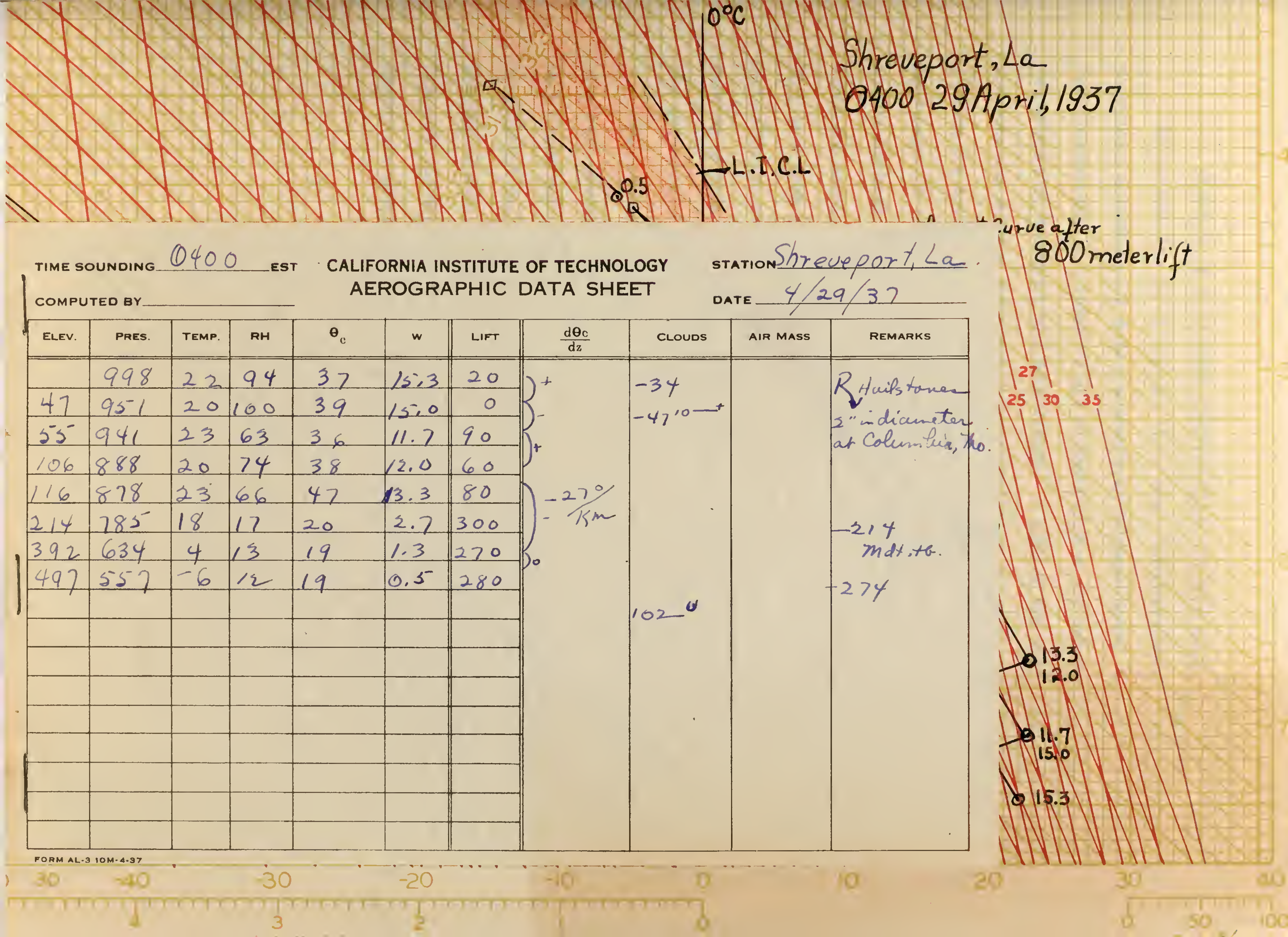
The sounding for Murfreesboro, Tenn., shows that the condensation level lies below the ice crystal level. For the assumed small lift of 550 meters the corrected ascent curve shows a small positive area below the ice crystal level and a moderate size positive area extending from the ice crystal level to the top of the sounding. Precipitation should form as rain and no thunderstorm should occur but conditions approach those necessary for a mild thunderstorm. The rain must fall through a cold PC_2 layer having temperatures 10° to 20° below freezing, and must freeze and reach the ground as sleet. The instability of the TG_2 air caused the precipitation to be intermittent. Scattered sleet and in some instances glazing or freezing of rain after reaching the ground occurred over several states.



(A.M.)
29 APRIL, 1937



(A.M.)
30 APRIL, 1937



Shreveport, La
0400 29 April, 1937

TIME SOUNDING 0400 EST

CALIFORNIA INSTITUTE OF TECHNOLOGY
AEROGRAPHIC DATA SHEET

STATION Shreveport, La.

COMPUTED BY

DATE 4/29/37

ELEV.	PRES.	TEMP.	RH	θ_c	W	LIFT	$\frac{d\theta c}{dz}$	CLOUDS	AIR MASS	REMARKS
	998	22	94	37	15.3	20	+	-34		R Hailstones 3" in diameter at Columbia, Mo.
47	951	20	100	39	15.0	0	-	-47'0		
55	941	23	63	36	11.7	90	+			
106	888	20	74	38	12.0	60				
116	878	23	66	47	13.3	80	-27°/Km			
214	785	18	17	20	2.7	300	-			-214
392	634	4	13	19	1.3	270	0			Mdt. tb.
497	557	-6	12	19	0.5	280				-274
								102		

FORM AL-3 10M-4-37

[illegible] THUNDERSTORMS AND COLD FRONT

Tornado Kills Woman, Cousin

Missouri Visited By Wind, Hail Storm

KANSAS CITY, Mo., Apr. 29. (U.P.)—Two persons were killed today and three children injured when a tornado destroyed three houses near Ash Grove, Mo.

Many sections of Western Missouri suffered damage by violent hail storms and local tornadoes.

Hits Farm House

Mrs. George Snyder and Elmer Corbin, a cousin, were killed when a tornado struck the Corbin farm house near Ash Grove.

Two children of Mrs. Snyder were reported injured. A small baby in another home nearby was blown clear and only slightly hurt when the house was wrecked.

Hail stones more than two inches in diameter gave Columbia its worst ice storm since 1913. Little damage was reported. A similar storm did some damage to automobiles in Kansas City.

Church Damaged

At Carrollton, Mo., tornadic winds destroyed several barns and houses and blew a church off its foundation. Trees and telephone and telegraph lines also suffered.

Another twister cut a swath through North Central Missouri, including communities around Breckenridge and Tatesville. Railway telegraph lines were down and barns were unroofed all along the tornado's path.

r

the west and the

urred over most of

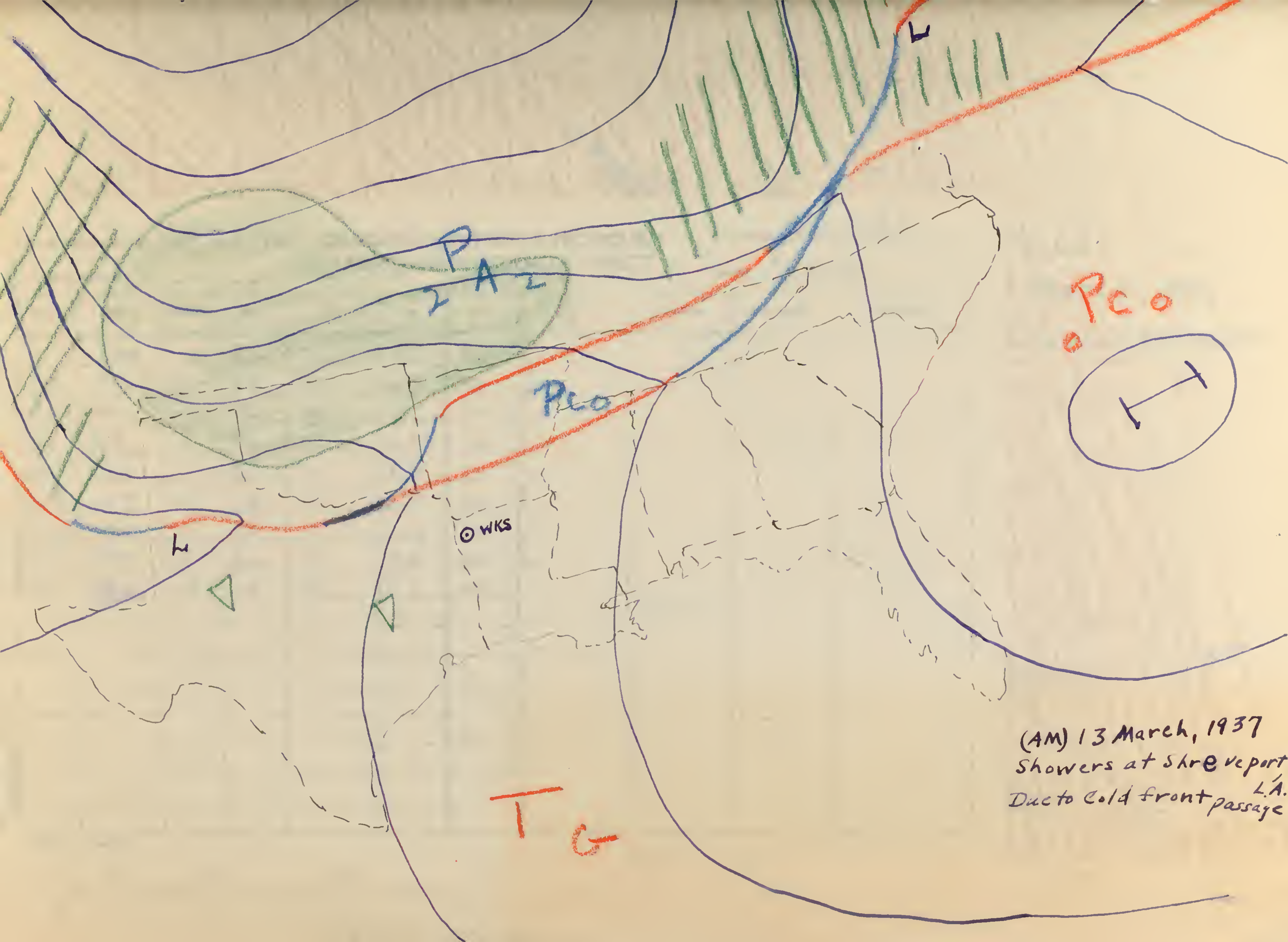
bia, Missouri,

ssouri during the day.

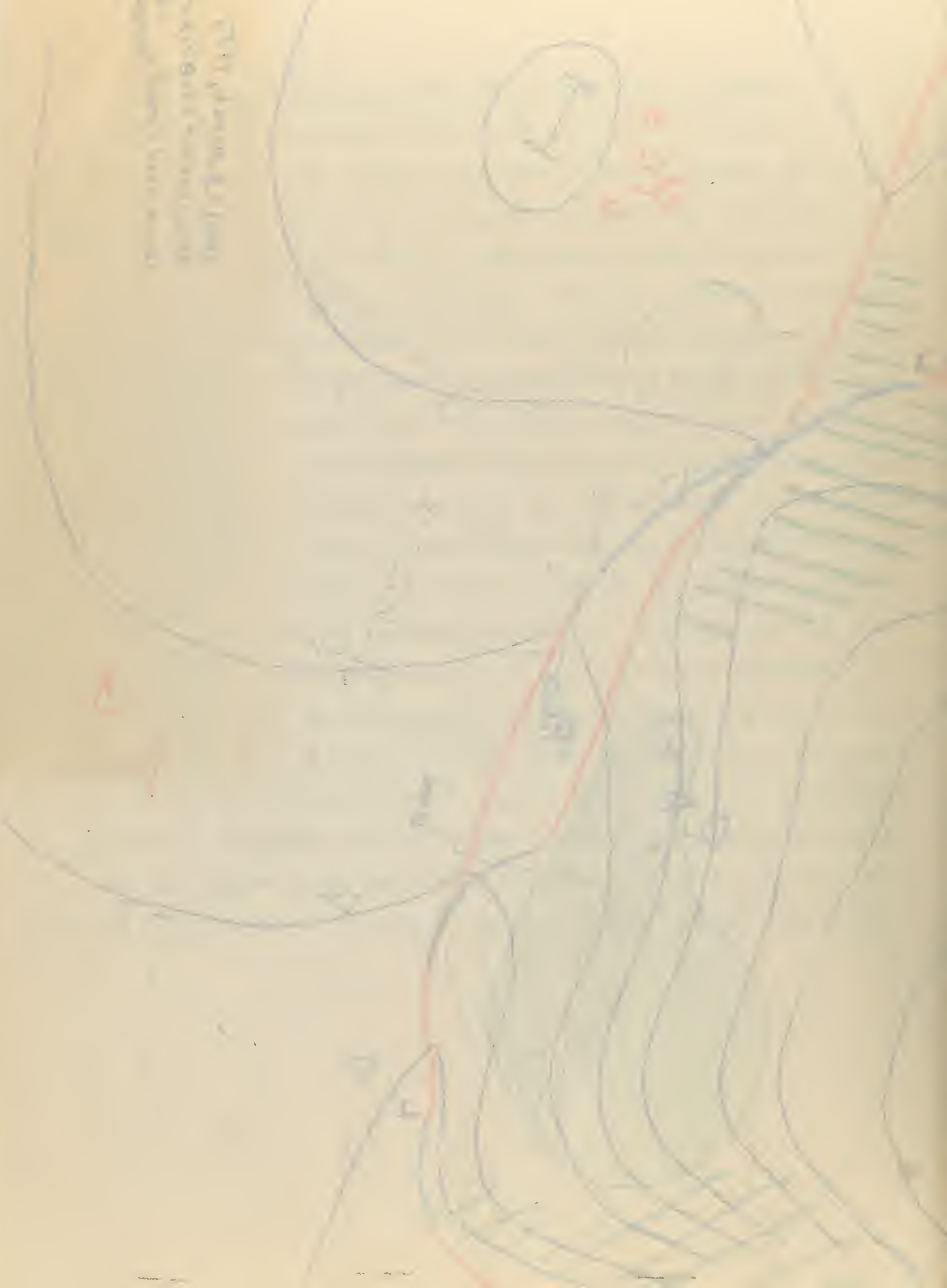
EXAMPLES OF WARM FRONT THUNDERSTORMS AND COLD FRONT THUNDERSTORMS

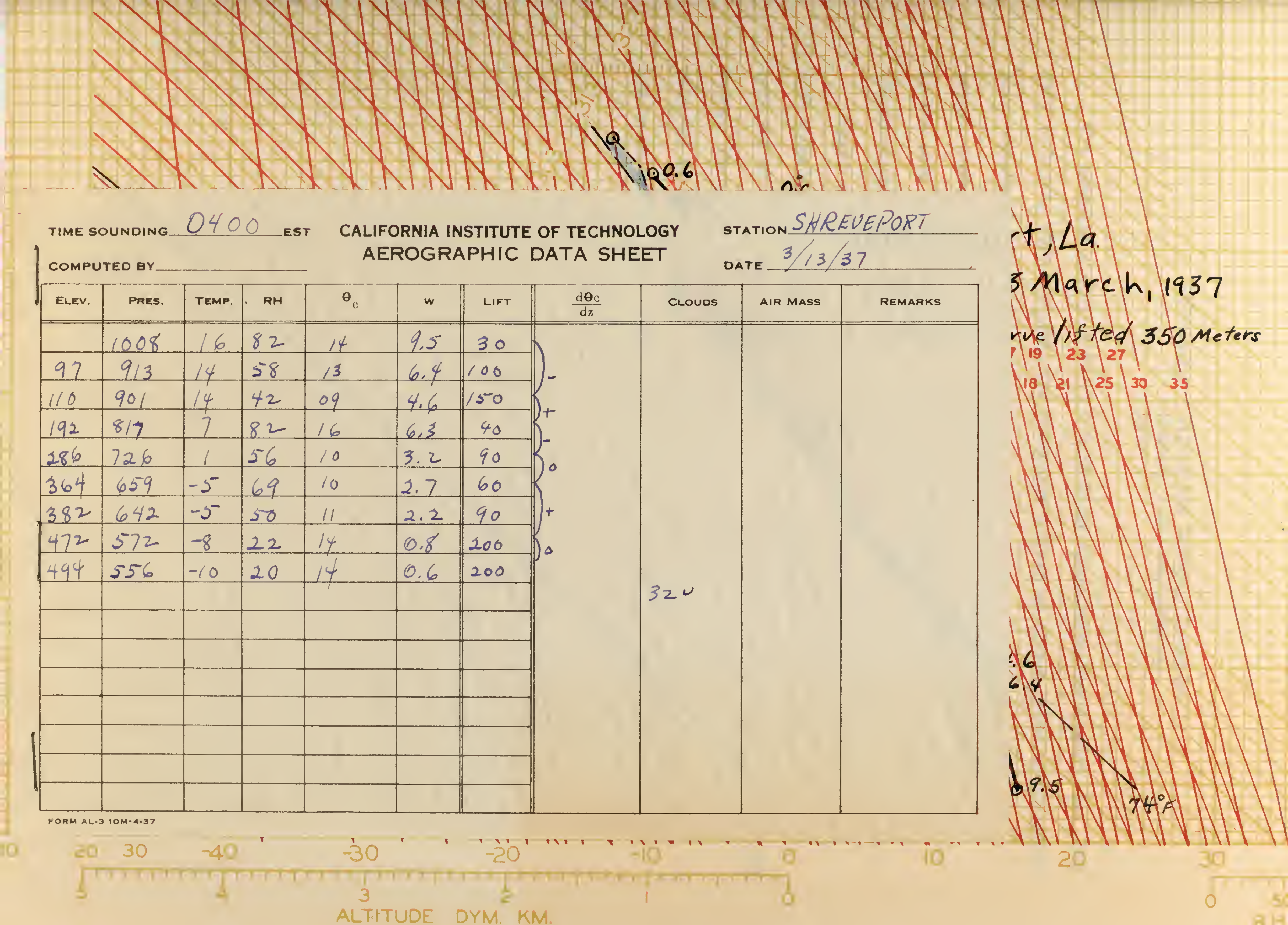
The weather map for 29 April, 1937, shows thunderstorms occurring along a warm front extending SSW from a center near Oklahoma City. The 0400 sounding for Shreveport, La., shows TG air having almost a dry adiabatic lapse rate above two kilometers occupying the warm sector. A lift of 800 meters is required to saturate and release the potential instability of a layer of 1200 meters. The lifting ice crystal level is situated so that there is a fairly large positive area below it--enough to probably insure a vertical velocity 8 meters per second at the ice crystal level and a large positive area above the ice crystal level keeps the acceleration and the velocity increasing rapidly up to high levels. This is a case similar to type five of the classifications of instability phenomena and calls for violent thunderstorms with hard hail since the approach of overrunning of this TG_1 air over the warm front and the approach of a cold front from the West should certainly lift the air the required 800 meters.

Thunderstorms continued along the warm front but due to the rapid SE movement of a high pressure wedge over NE United States all except a small portion of the warm front near the center became a cold front so that TG_1 air in the warm sector in Missouri was squeezed by the approach of a cold front from the west and the retrograde warm front in the east. Violent thunderstorms occurred over most of Missouri and hail stones two inches in diameter fell at Columbia, Missouri, during the afternoon. Several Tornadoes also occurred in Missouri during the day.



(AM) 13 March, 1937
Showers at Shreveport L.A.
Due to Cold front passage





TIME SOUNDING 0400 EST

CALIFORNIA INSTITUTE OF TECHNOLOGY
AEROGRAPHIC DATA SHEET

STATION SHREVEPORT

COMPUTED BY

DATE 3/13/37

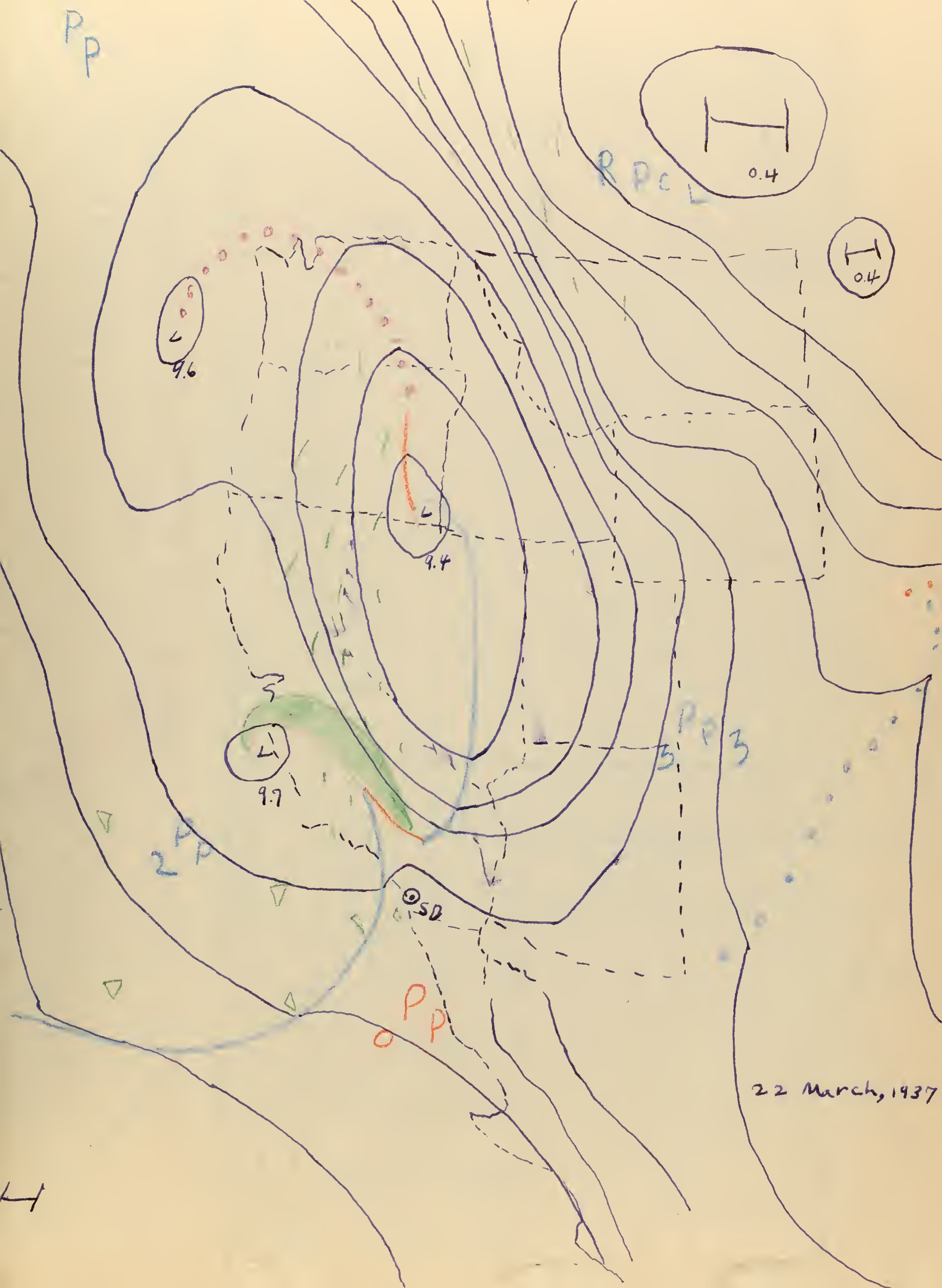
ELEV.	PRES.	TEMP.	RH	θ_c	W	LIFT	$\frac{d\theta c}{dz}$	CLOUDS	AIR MASS	REMARKS
	1008	16	82	14	9.5	30				
97	913	14	58	13	6.4	100	-			
110	901	14	42	09	4.6	150	+			
192	817	7	82	16	6.3	40	-			
286	726	1	56	10	3.2	90	o			
364	659	-5	69	10	2.7	60				
382	642	-5	50	11	2.2	90	+			
472	572	-8	22	14	0.8	200	o			
494	556	-10	20	14	0.6	200				
								32		

FORM AL-3 10M-4-37

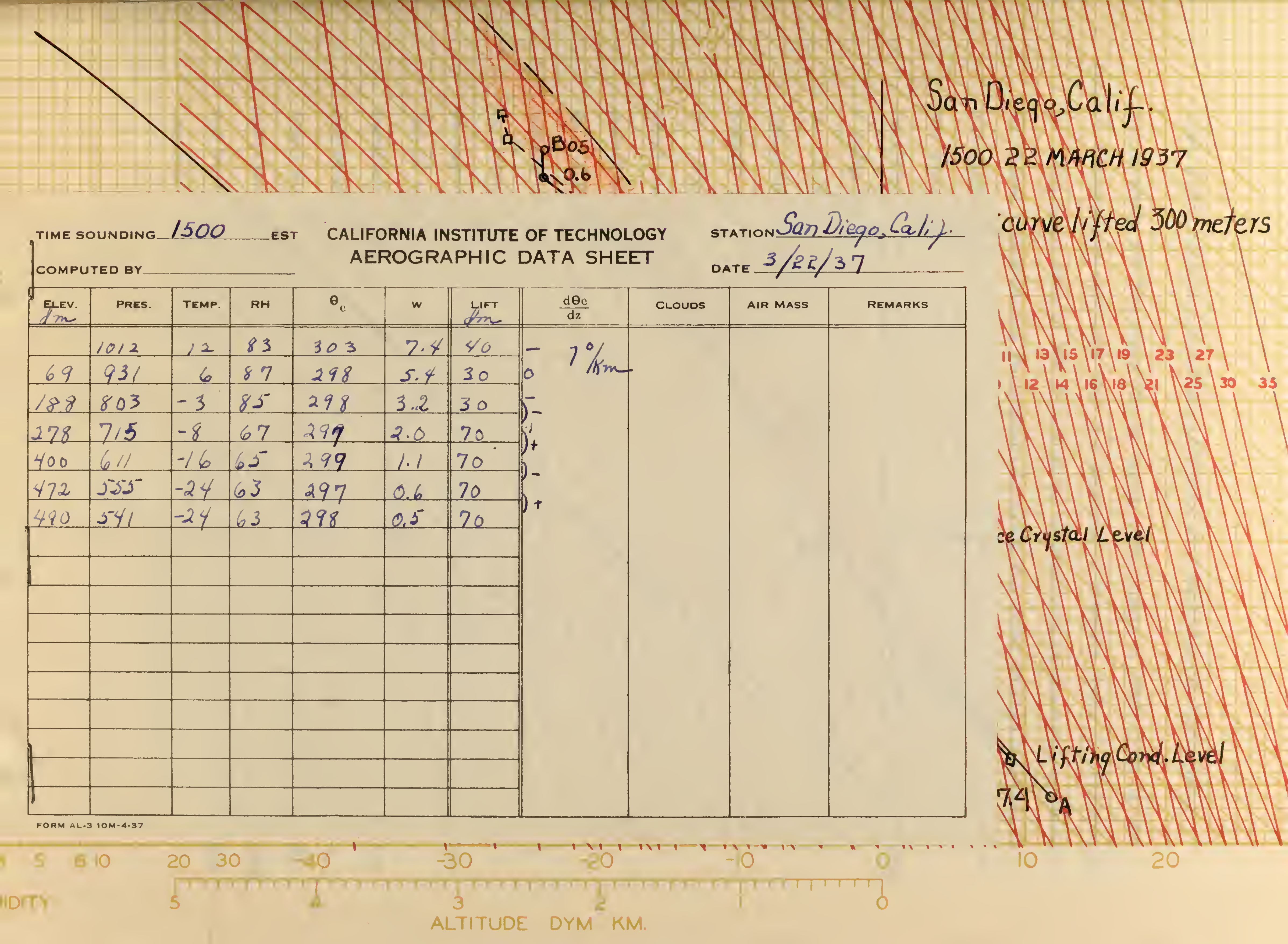
Cold Front - Lifted Air Becoming Unstable.
- Showery Type Precipitation.
- Rain

The synoptic situation shows a cold front approaching Shreeveport, La. The 0400 13 March, 1937, sounding for Shreeveport shows an ascent curve with several thin potentially unstable layers $\left(\frac{d\theta_e}{dz} < 0\right)$. The ascent curve lifted 350 meters shows a small positive area extending just below the ice crystal level to the 4200 meter level which seems to be of the type favoring showers but no thunderstorm since the positive area below the ice crystal level is very small.

Light intermittent showery type rain occurred during the early afternoon with moderate turbulence just before the frontal passage. No thunderstorm occurred at Shreeveport although scattered thunderstorm occurred in North Central Texas. No soundings are available for Texas but it is believed that the air reaching Texas had more of a Gulf trajectory than the air reaching Shreeveport and hence had a steeper lapse rate which would make it more unstable.



22 March, 1937


San Diego, Calif.
1500 22 MARCH 1937

curve lifted 300 meters

ce Crystal Level

Lifting Cond. Level

TIME SOUNDING 1500 EST

COMPUTED BY

CALIFORNIA INSTITUTE OF TECHNOLOGY
AEROGRAPHIC DATA SHEET

STATION San Diego, Calif.

DATE 3/22/37

ELEV. dm	PRES.	TEMP.	RH	θ_c	W	LIFT dm	$\frac{d\theta c}{dz}$	CLOUDS	AIR MASS	REMARKS
	1012	12	83	303	7.4	40	– 7°/km			
69	931	6	87	298	5.4	30	0			
188	803	-3	85	298	3.2	30	–)–			
278	715	-8	67	297	2.0	70	)+			
400	611	-16	65	299	1.1	70	)–			
472	555	-24	63	297	0.6	70	)+			
490	541	-24	63	298	0.5	70				

FORM AL-3 10M-4-37

COLD FRONT - LIFTED AIR BECOMING UNSTABLE-----THUNDERSTORM (SOFT HAIL)

The sounding for San Diego for 22 March, 1937, taken at 1500, just 3½ hours after a thunderstorm with soft hail had occurred at Pasadena shows the following:-

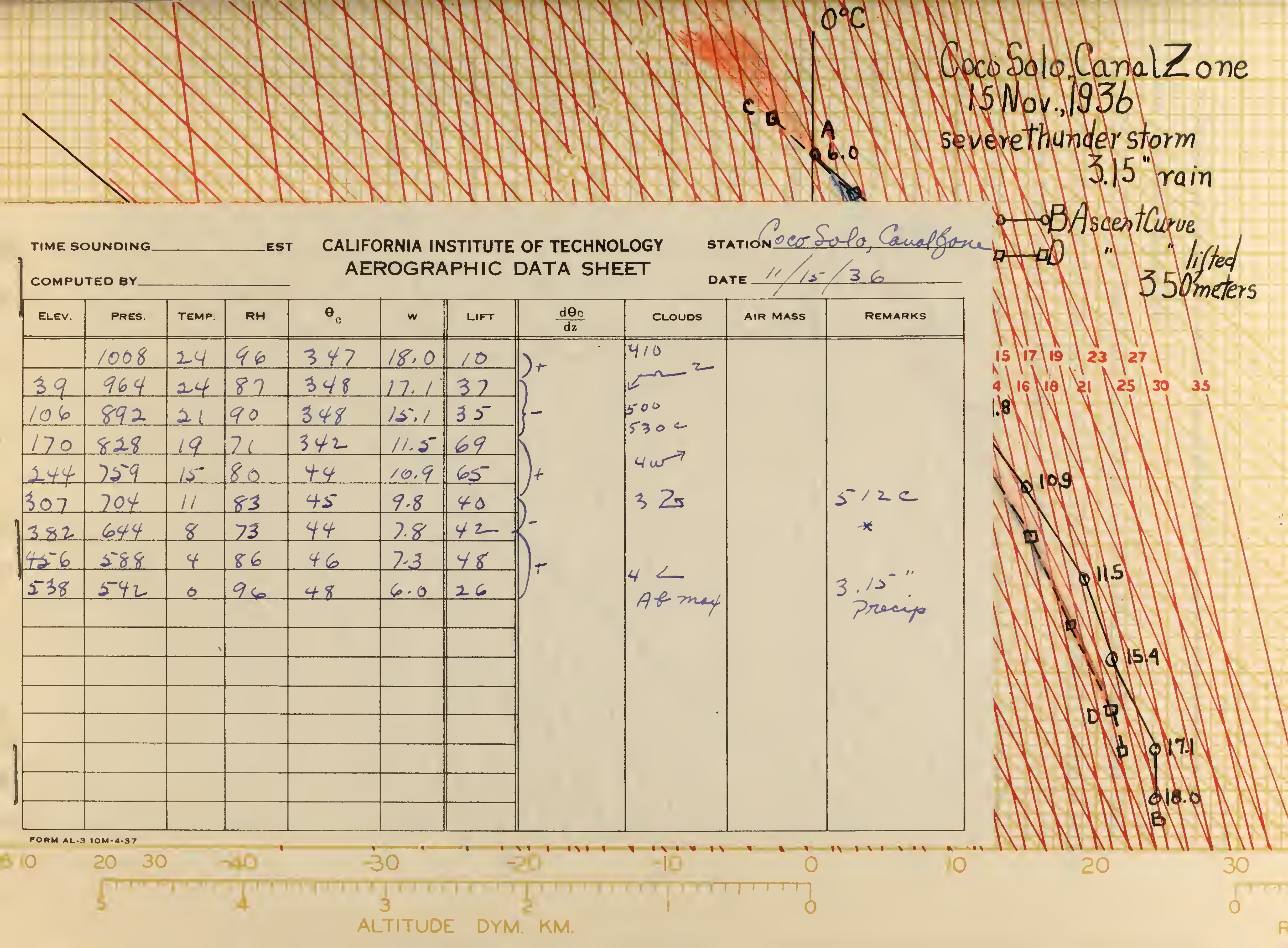
1. The lapse rate of the lifted curve is greater than the moist adiabatic up to 3.3 kilometer and is practically along the moist adiabatic beyond 3.3 kilometer. The unlifted ascent curve shows by a negative value of $\frac{d\theta_e}{dz} = 7^\circ$ per kilometer for the surface layer and by the small lift necessary to saturate the surface point that it is potentially unstable and should develop a large positive area.

2. A large positive area is formed between the lifted ascent curve and the moist adiabatic along which the first point to become saturated (the lowest) rises if about a 300 meter lift is provided.

3. Sufficient positive area is available below the lifting ice crystal level to probably insure a velocity somewhat greater than 8 meters per second at the level.

4. A large positive area extends for several kilometers beyond the ice crystal level.

5. Due to the above factors a thunderstorm with some form of hail would be expected. Comparing this sounding with the sounding for Shreveport, La. for 29 April, 1937, which indicated severe hail storms for Missouri and resulted in hailstones two inches in diameter, we see that the positive area and hence the acceleration of the rising layer is still increasing at a rapid rate in Shreveport sounding. In the San Diego sounding, however, the positive area seems to be decreasing. This leads to the belief that the size and vertical extent of the positive area above the ice crystal level are the factors which determine the type of hail storm which will result.



Coco Solo, Canal Zone
15 Nov., 1936
severe thunderstorm
3.15" rain

TIME SOUNDING ______ EST

COMPUTED BY ______

CALIFORNIA INSTITUTE OF TECHNOLOGY
AEROGRAPHIC DATA SHEET

STATION Coco Solo, Canal Zone

DATE 11/15/36

ELEV.	PRES.	TEMP.	RH	θ$_c$	W	LIFT	$\frac{d\theta c}{dz}$	CLOUDS	AIR MASS	REMARKS
	1008	24	96	347	18.0	10	+	410		
39	964	24	87	348	17.1	37	−	2		
106	892	21	90	348	15.1	35		500 530 c		
170	828	19	71	342	11.5	69	+			
244	759	15	80	44	10.9	65		4w↗		
307	704	11	83	45	9.8	40	−	3 2s		5 12 c
382	644	8	73	44	7.8	42				*
456	588	4	86	46	7.3	48	+	4 ∠		
538	542	0	96	48	6.0	26		Ab may		3.15" Precip

FORM AL-3 10M-4-37

Example of thunderstorm with precipitation as heavy rain caused by cold front approach and passage.

The sounding for Coco Solo, Canal Zone for 15 November, 1936, shows high relative humidities for the entire ascent. There are potentially instable layers from 390 to 1700 meters and from 3070 to 3820 meters.

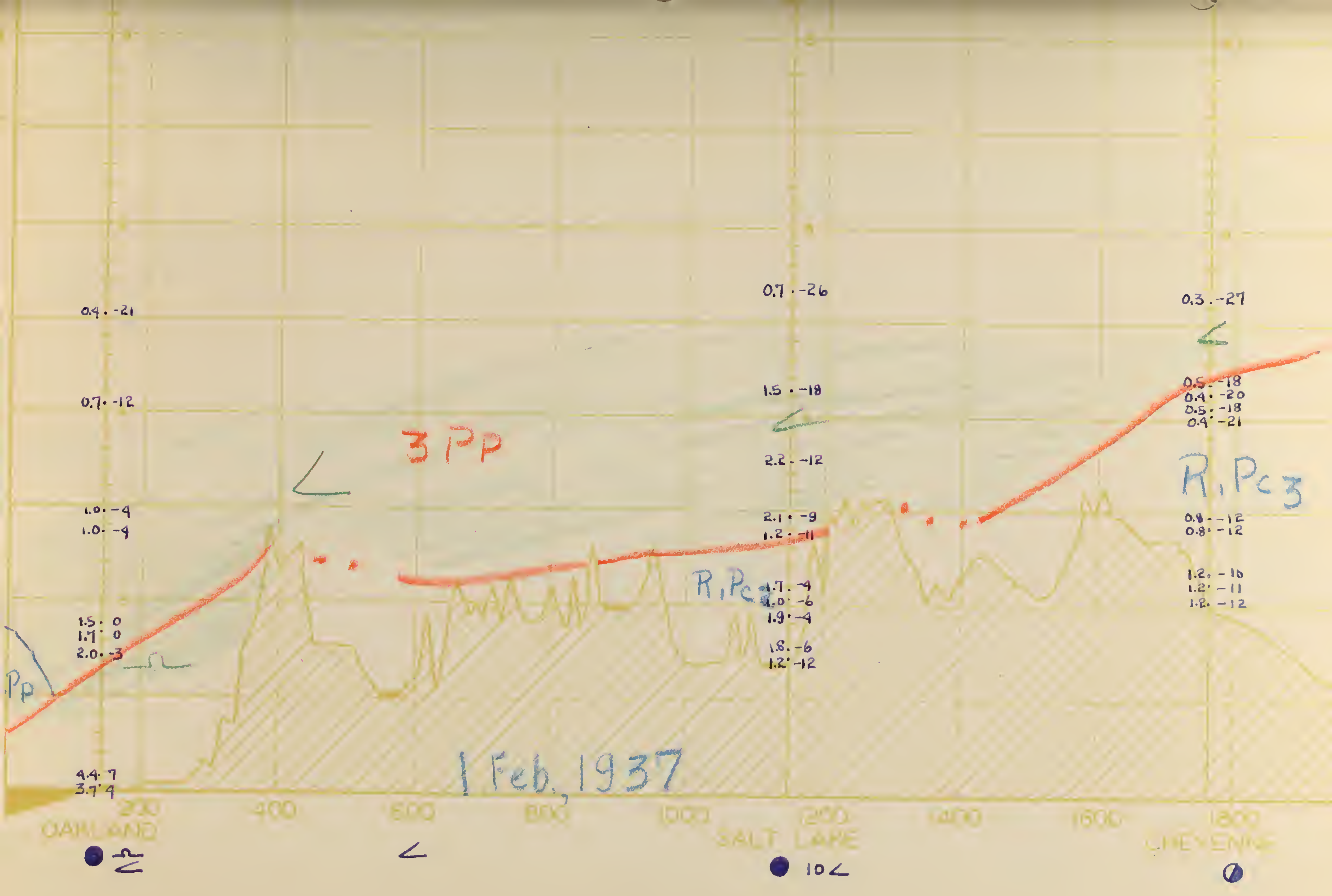
The action of 20% convergence alone would be sufficient to initiate free convection from the 1060 meter level and to form a positive area extending upward for the entire height of the sounding and containing the ice crystal level near the top.

The action of 10% convergence would require in addition only a 200 meter lift to produce free convection and a positive area as large as in case of 20% convergence.

A lift of 350 meters alone would also establish a positive area of nearly the same size and position.

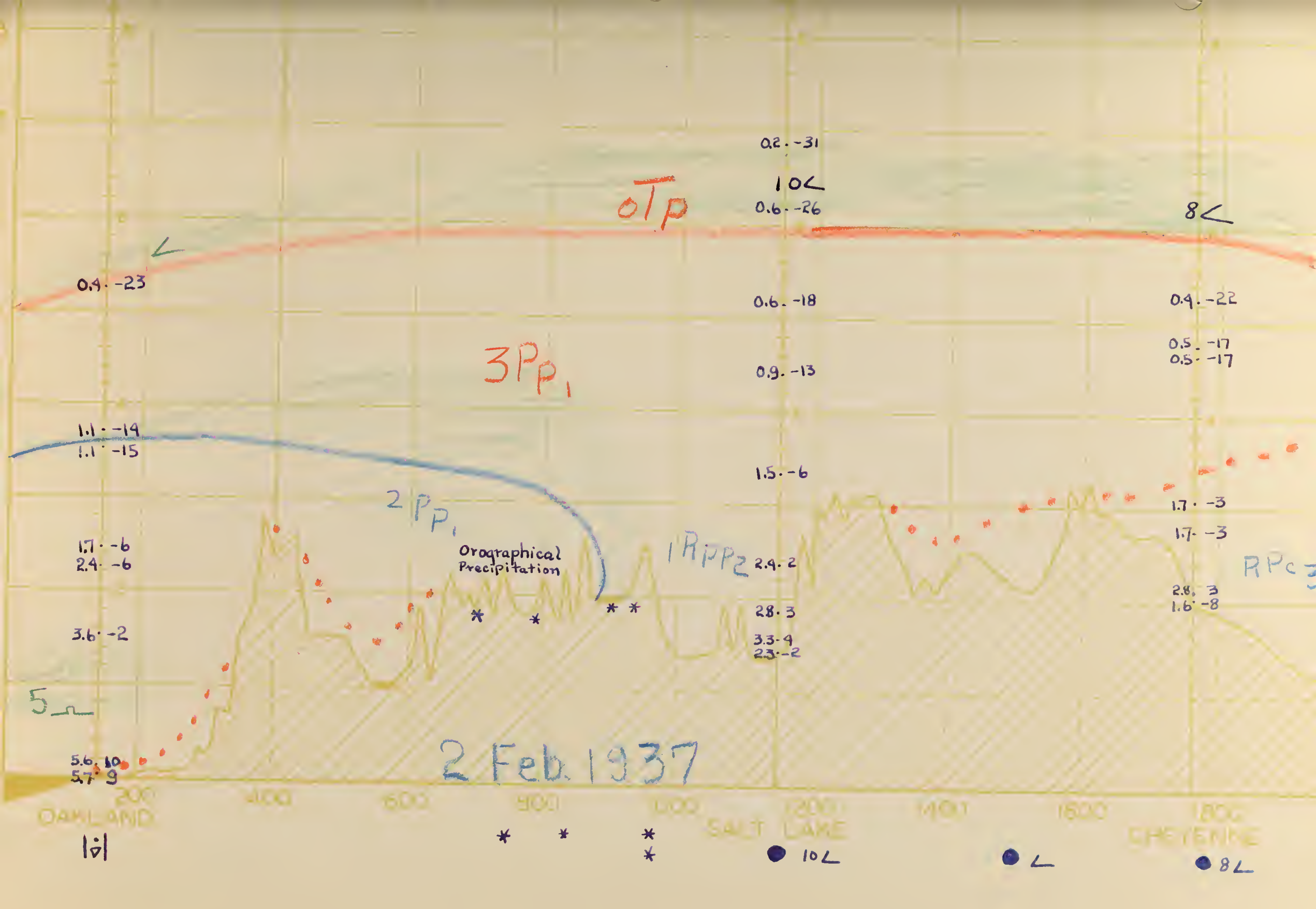
Since both lifting and convergence will be present with the approach and passage of the cold front it would appear that the potential instability could be realized. Orographical lifting could even set off this thunderstorm for neighboring regions. In this case, however, since the air flow is from the Northeast, ie, from the ocean it seems probable that the orographical lift could not be obtained in the immediate vicinity of Coco Solo.

A severe thunderstorm with excessive lightening and with 3.15 inches of rain occurred at about the time of the passage of a cold front.

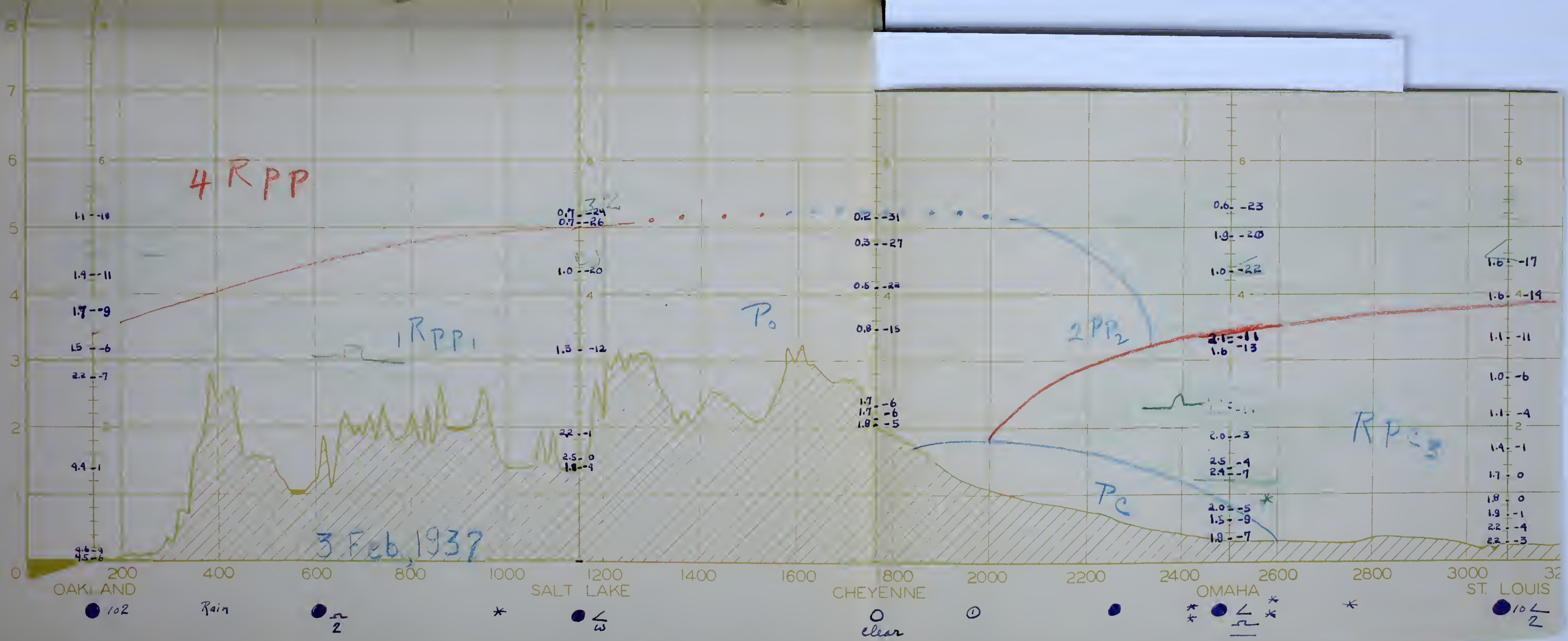


1 Feb, 1937

0.4 . -21
0.7 . -12
1.0 . -4
1.0 . -4
1.5 . 0
1.7 . 0
2.0 . -3
4.4 . 7
3.7 . 4
Pp
3 Pp
0.7 . -26
1.5 . -18
2.2 . -12
2.1 . -9
1.2 . -11
R, Pc
1.7 . -4
2.0 . -6
1.9 . -4
1.8 . -6
1.2 . -12
0.3 . -27
0.5 . -18
0.4 . -20
0.5 . -18
0.4 . -21
R, Pc 3
0.8 . -12
0.8 . -12
1.2 . -10
1.2 . -11
1.2 . -12
200
400
600
800
1000
1200
1400
1600
1800
OAKLAND
SALT LAKE
CHEYENNE
10


2 Feb. 1937

0.2. -31
10∠
0.6. -26
oTp
8∠
0.4. -23
0.6. -18
0.4. -22
0.5. -17
0.5. -17
3Pp1
0.9. -13
1.1. -14
1.1. -15
1.5. -6
2Pp1
1.7. -3
1.7. -3
1.7. -6
2.4. -6
Orographical Precipitation
1Rpp2
2.4. 2
RPc
2.8. 3
1.6. -8
28. 3
3.3. -4
2.3. -2
3.6. -2
5
5.6. 10
5.7. 9
200
400
600
900
1000
1200
1400
1600
1800
OAKLAND
SALT LAKE
CHEYENNE
10∠
∠
8∠


4 RPP
1RPP1
Po
2PP2
Pc
RPc3
0
2
3
4
5
6
7
8
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
32
OAKLAND
SALT LAKE
CHEYENNE
OMAHA
ST. LOUIS
1.1 - -18
1.9 - -11
1.7 - -9
1.5 - -6
2.2 - -7
4.4 - 1
4.6 - 9
4.5 - 6
0.7 - -24
0.7 - -26
1.0 - -20
1.3 - -12
2.2 - -1
2.5 - 0
1.8 - -4
0.2 - -31
0.3 - -27
0.5 - -22
0.8 - -15
1.7 - -6
1.7 - -6
1.8 - -5
0.6 - -23
1.9 - -20
1.0 - -22
2.1 - -11
1.6 -13
2.0 - -3
2.5 - -4
2.4 - -7
2.0 - -5
1.5 - -9
1.8 - -7
1.6 - -17
1.6 - -14
1.1 - -11
1.0 - -6
1.1 - -4
1.4 - -1
1.7 - 0
1.8 - 0
1.9 - -1
2.2 - -4
2.2 - -3
102
Rain
2
ω
clear
10
2

3 Feb 1937

OCCLUSIONS

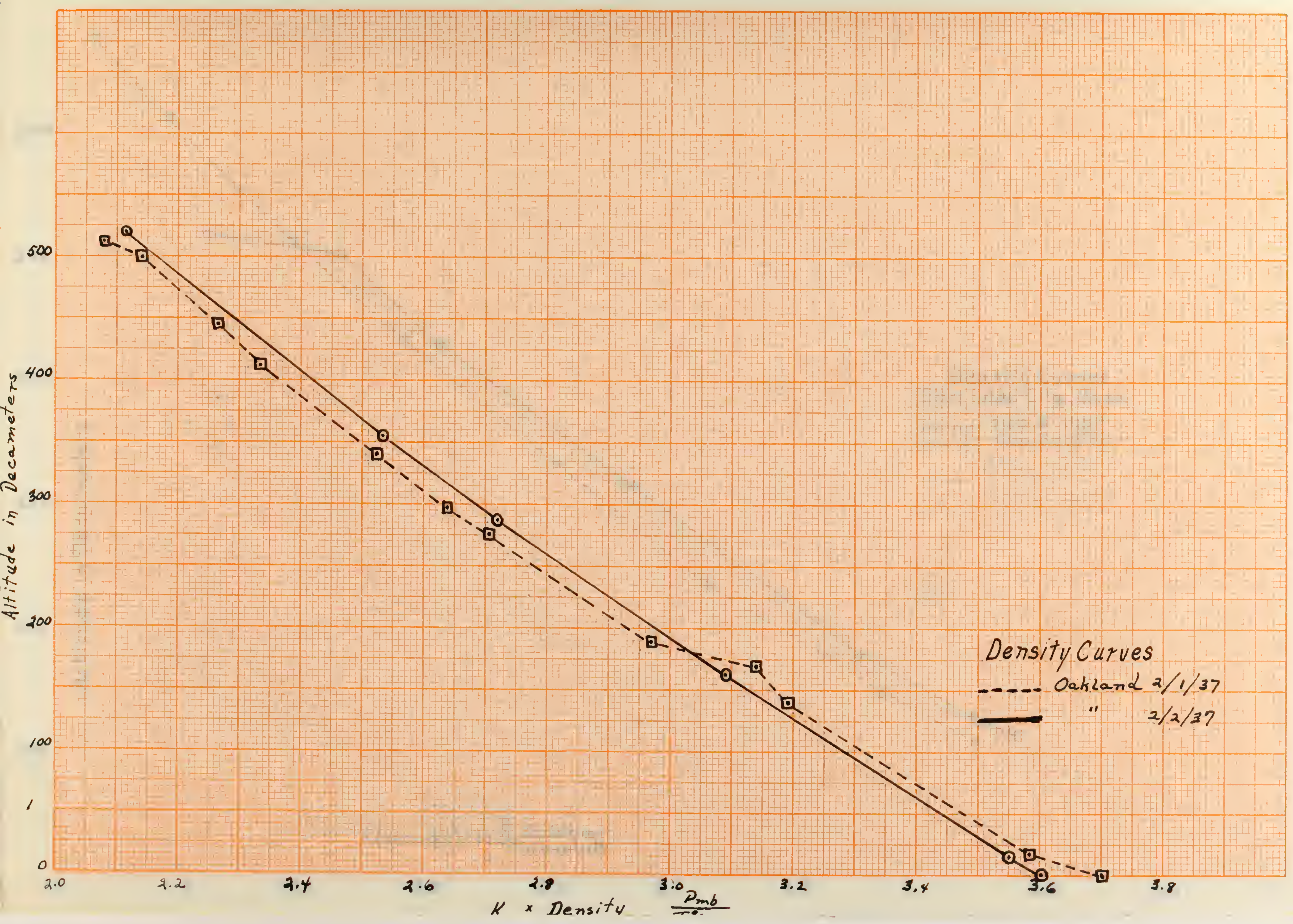
In considering occluding systems it is important to know whether the occlusion will be of the warm or of the cold front type. In the cold front type occlusion the approaching air behind the cold front is colder than either the air in the warm sector or the air under the warm front surface so that the cold front displaces the warm sector air forcing it aloft, ie, occluding it, and the cold front continues as a surface cold front displacing the air which was under the warm front.

In the case of the warm front type occlusion the approaching cold air behind the cold front has not a density as great as that of the air under the warm front so it can not displace this air at the surface and can only displace the warm sector air, then moved aloft as an upper cold front.

Quite often otherwise unexplainable clouds and rain pattern may be attributed to the action along an upper cold front. It is of interest therefore to be able to detect upper cold fronts. Holzman has published a paper on this subject in the Monthly Weather Review, December, 1936. The following interesting situation is along the general lines of this article. Since an upper cold front owes its origin to a warm front (ie, upper cold front) occlusion, and since upper cold fronts may be located much more readil if previous synoptic situations have indicated the future presence of one, the ideal method of approach is to determine before hand whether an occluding system will be of the warm or of the cold front type.

If the temperature contrast is large between the approaching cold front of the wave and the cold air under the warm front of the wave then it is possible to tell by inspection which type of occlusion will result, but when the contrast is small then the densities of the two air masses must be compared.

At present, soundings from ships at sea in the approaching air mass are seldom available, in the following example it was necessary to use the soundings at Oakland,


Density Curves
Oakland 2/1/37
" 2/2/37
Altitude in Decameters
500
400
300
200
100
1
0
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
K × Density Pmb

California, on two successive days when Oakland was in the two cold air masses whose densities it was desirable to compare. As pointed out by Holzman (7) the Valve $\frac{P}{T}$ of an air mass being proportional to density may be compared with $\frac{P}{T}$ at the same elevation in another air mass and by so doing a comparison of the densities of the two air masses is obtained. In the case of a cold front passage extending to the surface the $\frac{P}{T}$ or K(density) versus altitude curve for the cold air mass will indicate greater valves of density at all levels than a similar curve for the warm air.

Since cold fronts usually pass Oakland before reaching Southern California a comparison of the density curves for Oakland after a cold front passage with San Diego, will determine whether the cold front will pass the Los Angeles region as a surface front or as an upper cold front. In cases where a stratus overcast and drizzle condition exists in the Los Angeles region it may be very useful to determine whether or not an approaching cold front will have dense enough air behind it at the surface to displace the air characterized by overcast and drizzle. In case of an upper cold front passage some precipitation of a heavier type may occur but overcast and drizzle continues until either an offshore gradient of pressure develops or a displacement of the air present by a denser air mass occurs.

In case of a warm front passage the $\frac{P}{T}$ or K (density) curve for the warm air will indicate at all levels less density than a similar curve for the cold air under the warm front.

In case of a cold front type occlusion the $\frac{P}{T}$ vs altitude curve for the air behind the cold front will indicate greater density at all levels than a similar curve for the cold air under the warm front and the cold front will move along the surface and not be forced aloft.

In case of a warm front type occlusion the $\frac{P}{T}$ vs altitude curves will cross if the sounding in the air under the warm front goes high enough to penetrate the warm front. This will show that the approaching cold air is less dense than the cold air, under the warm front but that it is moredense than the warm air and will therefore climb along the warm front surface as an upper cold front. This idea may be carried further. If $\frac{P}{T}$ vs altitude curves plotted for two successive days at the same or nearby stations cross showing more dense air at upper levels than the air at upper levels than this is evidence of the passage of an upper cold front.

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(7) (B. Holzman - Monthly Weather Review Vol. 64 - December, 1936, Pages 400 - 414.)

The morning weather map for 1 February, 1937, shows an occlusion just off the Washington, Oregon and Northern California Coast with one PP air approaching while Cold RPC air would not be as cold as the RPC air and therefore a warm front type occlusion would occur. There is some evidence of an upper cold front in Washington and Oregon, chiefly the slight differential in pressure at the surface is a means of locating the surface projection of the upper cold front.

The $\frac{P}{T}$ vs altitude curves for Oakland, California, for 1 February and for 2 February (figure) show the characteristic crossing indicative of the passage of an upper cold front.

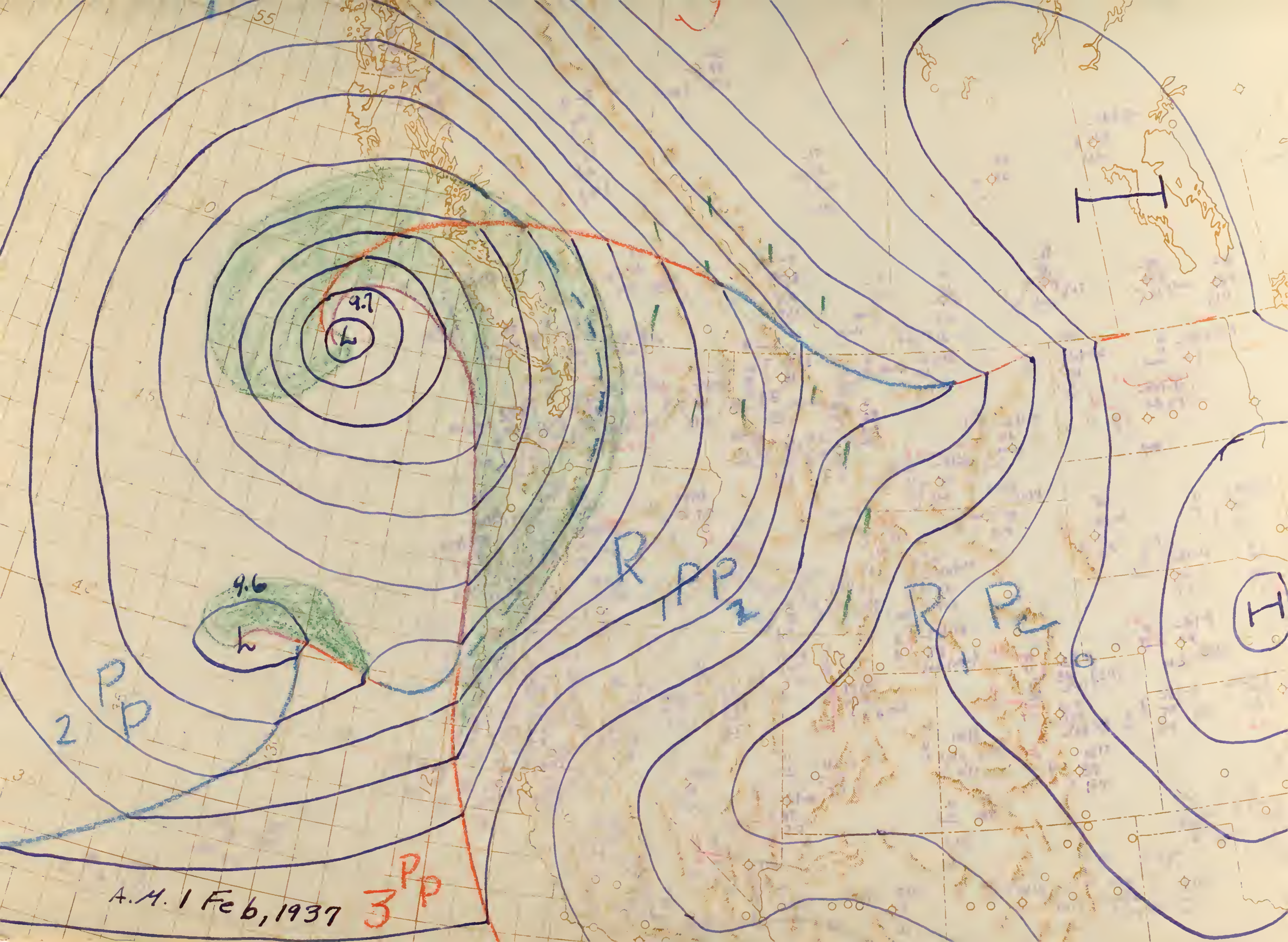
This crossing of the curves at approximately 1800 meters indicates the approximate level of the upper cold front. Since this level is above the elevation of most of the mountain plateau the upper cold front becomes a surface cold front over the mountains. The density curves for Salt Lake City, Utah, for 2 and 3 February, 1937, show denser air at the surface extending up to about five kilometers. Above this level the curve for 3 February shows the air to be less dense. This simply shows that at this level the sounding has encountered warmer and less dense air over-running from the West. A comparison of the density curve for Oakland for 2 February in the air under the upper cold front with the density curve for Salt Lake City for 2 February in $_1RPP_2$ air (~~figure #~~) shows the Oakland air to be denser level for level than the Salt Lake City air. Therefore a surface frontal passage will occur.

Precipitation has occurred in the form of moderate rain at Oakland and moderate to light snow fell in the mountains to the East, the precipitation being heaviest in the vicinity of the upper front.

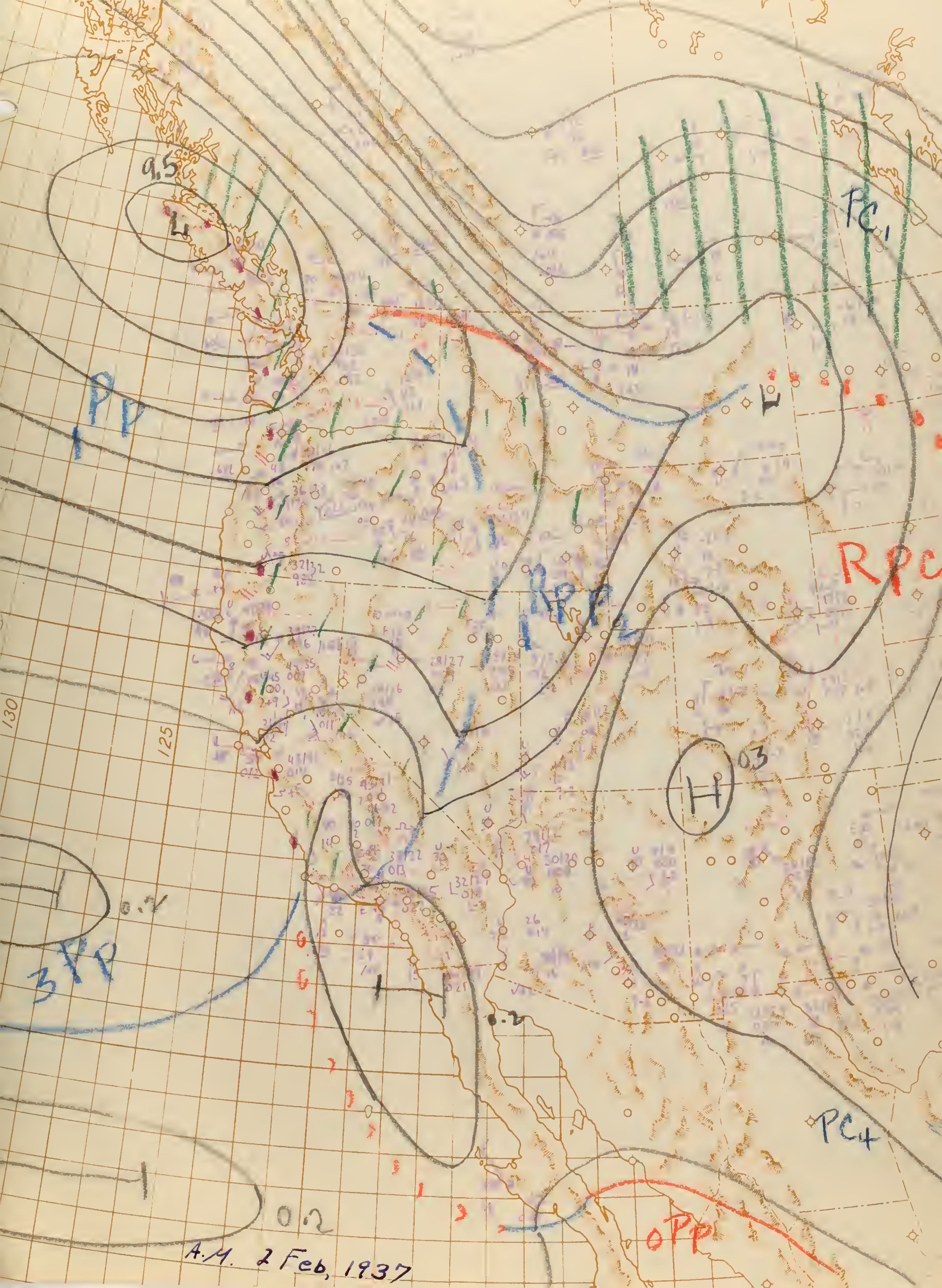
A little precipitation occurred as light snow in the mountains East of Salt Lake City. Cheyenne experienced no precipitation due largely to the effects of subsidence in this region. East of Cheyenne the frontal system was regenerated somewhat.

On 3 February, East of the mountains, a cold front was forced Southward by the buildup of a wedge of high pressure. On the upper air cross section sketch for 3 February this shows up as a wedge of PC air at the ground.

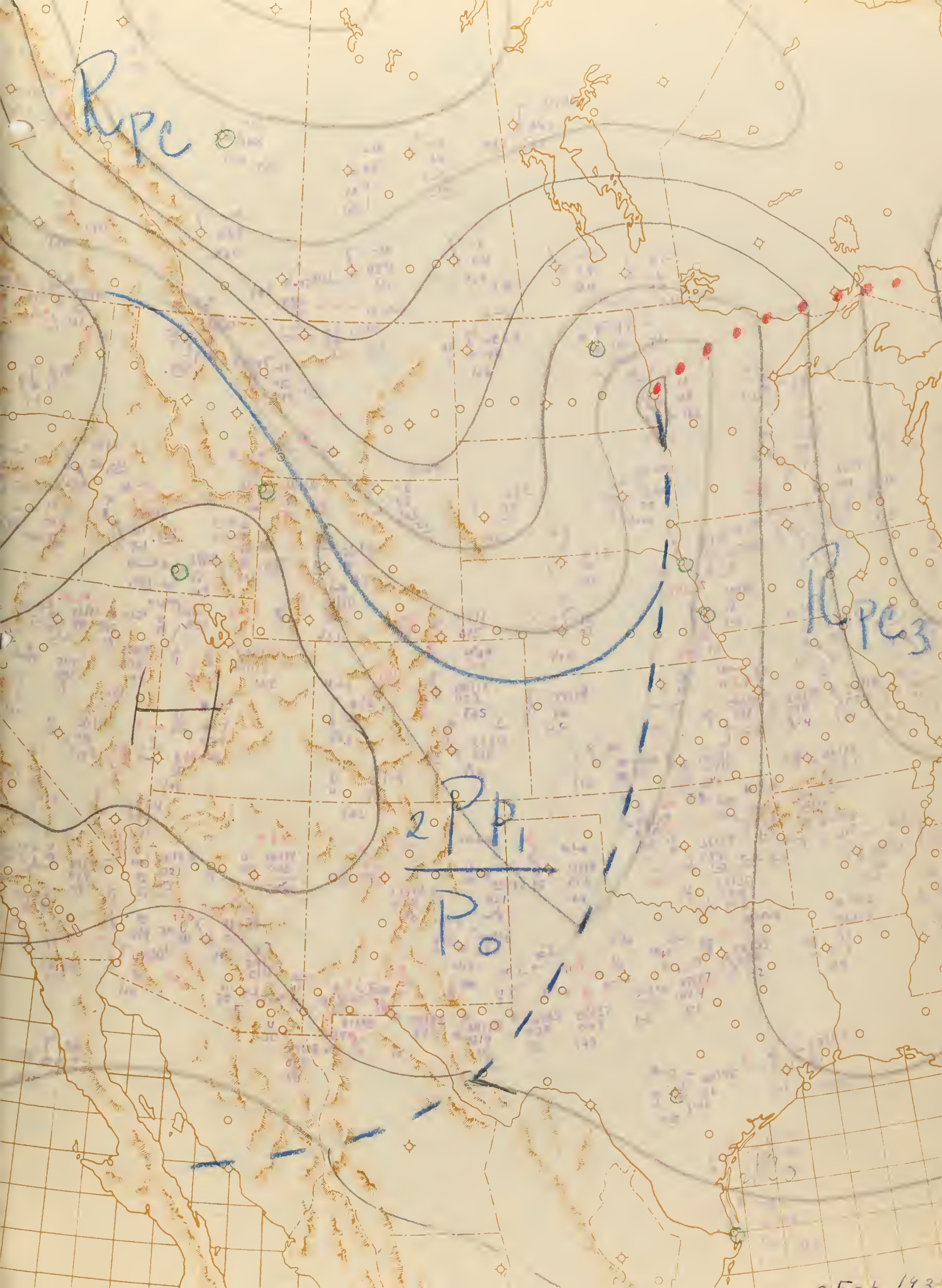
Moderate precipitation in the form of snow occurred in the vicinity of Omaha.



A.M. 1 Feb, 1937



A.M. 2 Feb, 1937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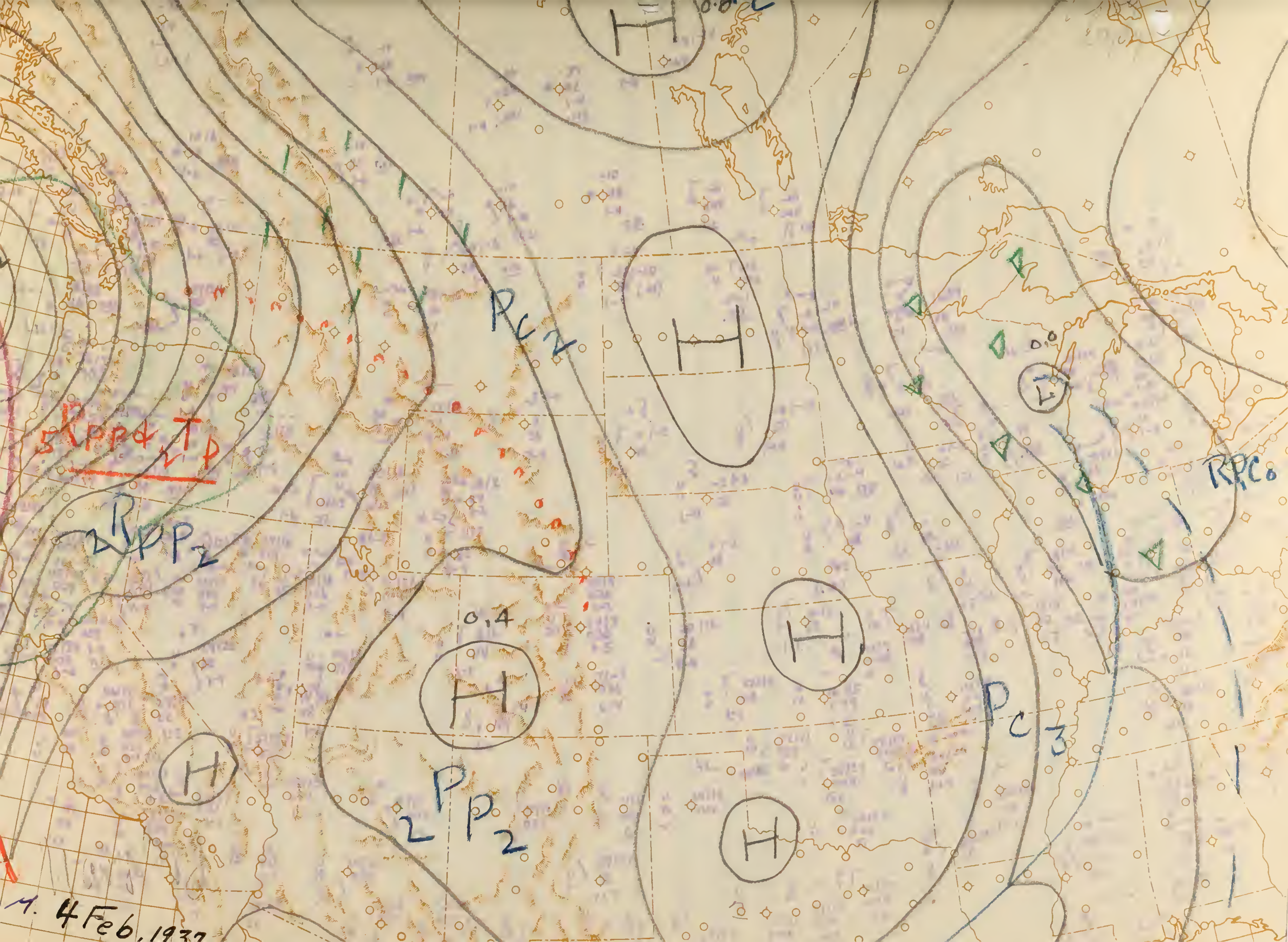

M. 4 Feb. 1937

East of the mountains the front again becomes an upper cold front. The density curves for Murfreesboro, Va. for 3 and 4 February, 1937, cross in the characteristic manner showing the surface air to be less dense on 4 February than on 3 February while above 1500 meters the air present on 4 February is denser than that above this level on the previous day.

The upper front becomes very diffuse near Shreveport, La. but even there the same characteristic crossing of the density curves for before and after the passage of an upper cold front occurs. In this case, however, the two curves lie practically along each other from 1200 meters to 3300 meters showing practically no difference in density between these levels.

In the foregoing examples soundings before and after the passage of an upper cold front were used to show that an upper cold front had passed. To be thoroughly useful this method would require simply a comparison of $\frac{P}{T}$ vs altitude curves prepared from soundings anywhere within the air mass behind the cold front which is occluding the warm sector of a cyclone and from any where at low levels in the cold air under the warm front. Since most cyclones occlude to a great extent before arrival at the Pacific Coast it would be highly desirable in certain cases to have soundings from ships in the approaching cold mass.

The most complex cloud systems that accompany warm front type occlusions occur during winter. In the initial stage a belt of alto-cumulus or alto-stratus may be noticed in advance of the surface shift, and the upper front may likewise be present; but as the cold wedge proceeds aloft there is a sudden thickening of the alto-stratus, and within one or two hours without any evidence whatsoever from Westward - lying stations a moderate snow condition may develop. A strato-cumulus layer generally will form beneath the lowering and thickening alto-stratus; and as precipitation continues, a low stratus deck eventually develops within the surface cold air mass, limiting ceilings to 500 - 1500 feet.

On the surface map the indications of the upper cold front are:

(1) A slight pressure trough which may not be noticeable unless the front is at comparatively low levels.

(2) Opposing surface winds in high level regions where the upper front is close to or on the ground.

(3) A zone of alto-cumulus or alto-stratus 100 to 500 miles in advance of the surface front may lead one to suspect the presence of an upper cold front but this can not be taken as conclusive. Usually a zone of alto-cumulus with little or no precipitation will mark the advance of an upper cold front in Spring and Autumn. In Summer a series of high level thunderstorms may serve to locate theregion in which an upper front lies.

CONCLUSION

Further study of the factors governing various types of precipitation would be greatly assisted by extensive use of the radio meteorograph since aircraft are unable to reach the levels at which many of the instability types of precipitation are formed.

Certain typical situations have been described which seem to be fairly well defined. There are many others, however, where a degree change in temperature or a gram per kilogram change in specific humidity at a critical level may mean the difference between precipitation or no precipitation, between a thunderstorm of one type and another, or the difference between precipitation as rain or as snow.

It is seen that a small error in the computation of or in the plotting up of a sounding may cause misleading conclusions to be made. A sounding may even be of negative value unless one considers the probable changes in the structure of the air due to expected orographical effects, convergence, divergence, frontal lifting, trajectory of the air, etc.

In certain cases it would be highly desirable to have a series of soundings made before, during, and after the formation of various types of precipitation in order to follow the steps in the formation of precipitation.

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